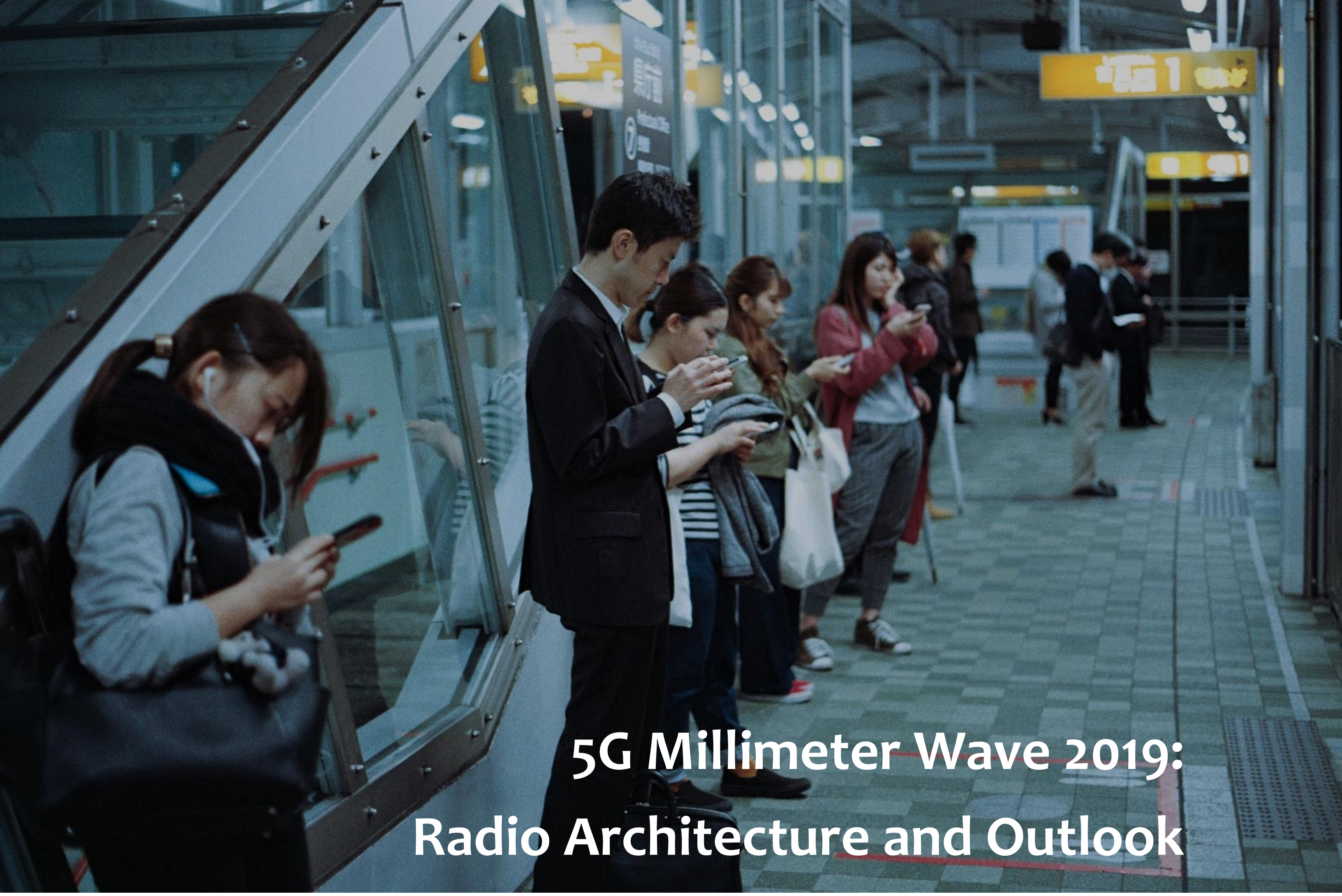

5G Millimeter Wave 2019:
Radio Architecture and Outlook

Abstract:

This report provides a complete view of 5G mm-wave networks, including architectural details for both networks and client devices. Key details of Massive MIMO implementation for high power/long range as well as indoor and repeater solutions are laid out. Many questions on RF implementation have now been answered in RRH and handset design, and detailed power consumption and cost analysis shows the likely choices of OEMs. Cost estimates for network and handset/hotspot implementation show the direction for operators. A forecast through 2025 includes base station and RRH deployment (macro and small cell), as well as CPEs, mobile handsets, hotspots, tablets, and IoT devices.

J. Madden

March 2019

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5G Millimeter Wave 2019:
Radio Architecture and Market Outlook

MEXP-5GMMWAVE-19
March 2019

1 Executive Summary

Three years ago, most RF engineers were extremely skeptical about the use of mm-wave bands in mobile networks. The handovers, propagation issues, and other technical challenges were considered difficult barriers. At the same time, consumer demand growth was not clear. Would mobile users grow to use 10 GB per month? 50 GB per month? 100 GB per month?

Today, these questions have answers. Field trials have proven that mm-wave coverage can be adequate to supplement the LTE network with a very effective offloading layer. Fixed wireless access trials have achieved both indoor and outdoor success, with gigabit speeds over hundreds of meters and effectively replacing FTTH or cable.

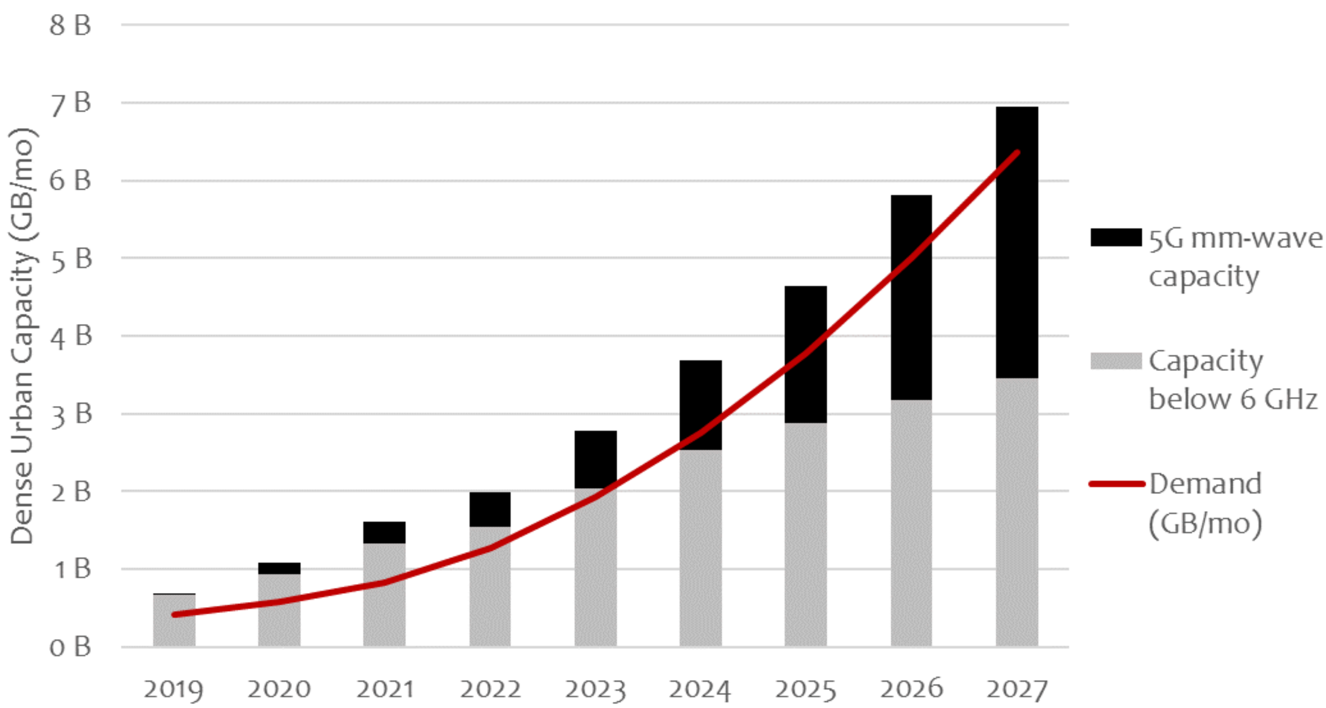

Figure 1 5G Strategic view: Necessary for mobile capacity

Source: Mobile Experts 5G Business Case Dec 2018

The appetite for mobile data has continued to increase, beyond all expectations. Websites and social media networks run videos automatically for mobile users, driving up usage. More importantly, we now see a growing number of people using smartphones as 'hotspots' to stream high-resolution video to big screens. For a small but important segment of young people, the LTE connection is their primary Internet connection. We expect this trend to continue, driving usage beyond the reach of LTE bands below 6 GHz. In short, 5G mm-wave will be *necessary* to keep up with urban data demand.

While 5G mm-wave will be necessary in cities, we don't expect mm-wave networks to ever be deployed nationwide. The cost of widespread coverage is simply too high. The broadband capacity is huge, but in rural locations it simply is not necessary during the next ten years.

Getting into the radio implementation for 5G mm-wave networks, we anticipate heavy use of massive MIMO with very high level arrays. Most gNodeB sites will use 256 elements per sector, streaming four streams. These numbers are likely to grow over time.

On the user side, 5G mm-wave smartphones are in development now, but they have cost and practical challenges. Foldable phones may help. Another possibility will be for 5G hotspots to be used by consumers, converting 5G mm-wave traffic to Wi-Fi or another local wireless connection.

The benefits of 5G mm-wave services will not be clear to the end user, because consumers are already getting gigabit LTE services with high-level Carrier Aggregation today. The rationale for 5G mm-wave is purely on the side of cost benefits for the operator. Therefore we expect the operators to incentivize their customers to move to mm-wave devices. Subsidies or free hotspots are in our future.

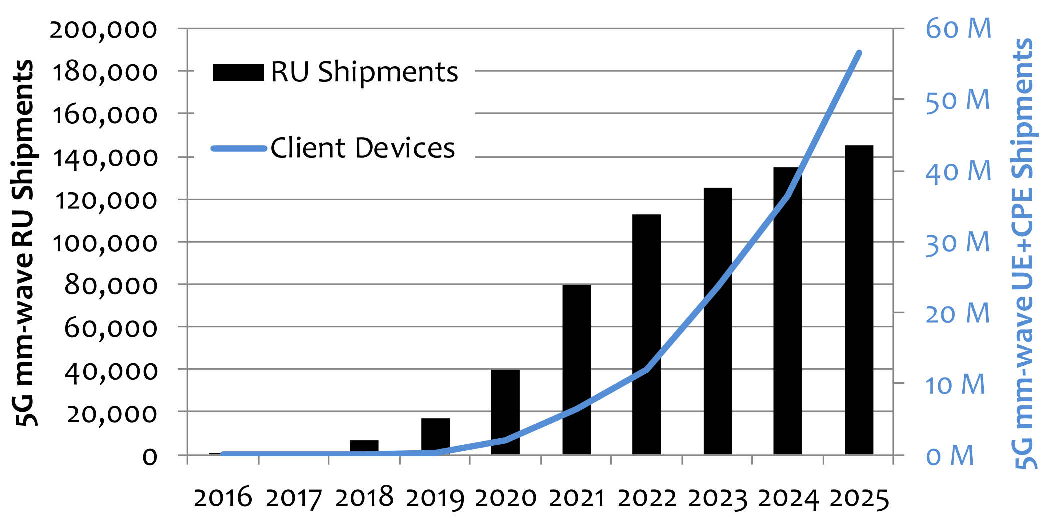

Chart 1: Forecasted 5G mm-wave network and user device shipments through 2025

Source: Mobile Experts

Worldwide, we expect many countries to use mm-wave technology eventually. During the next five years, the market will be concentrated in the USA and Korea, due to high density of traffic and high ARPU in these two markets. The USA is the prime market, mainly because of a shortage of spectrum in the 3-5 GHz range. Other countries will make use of mm-wave bands after they have fully exploited the 3-5 GHz bands… so the worldwide rollout could last through 2035 or even beyond.

2 MARKET DRIVERS AND CHALLENGES

The mobile market is driven by a simple equation: Operators need to drive down their cost per GB faster than the drop in retail price per GB. Don't get confused by Virtual Reality demos and self-driving cars. For the 5G mm-wave market, the single market driver comes down to a need to deliver huge truckloads of data, to consumers that will continue to pay only about $40-50 per month.

Market Drivers

Any operator that has other spectrum options will not invest in 5G mm-wave mobile networks. The cost to cover a large area can be staggering. But in the United States, the operators are squeezing every ounce of capacity out of their spectrum below 6 GHz. In our recent "5G Broadband Business Case" analysis, we analyzed the level of capacity that is achievable using 4-5 bands below 6 GHz, including Massive MIMO, small cells, LAA, and even new frequency bands.

The outcome of our capacity modeling shows that a 100 MHz block of spectrum in the 3-4 GHz range can be very useful in adding capacity to the network. Massive MIMO is less effective below 2 GHz because the frequency bands are relatively narrow, yielding less benefit for Massive MIMO. In addition, the large antenna size for lower frequency bands makes massive MIMO expensive below 2 GHz.

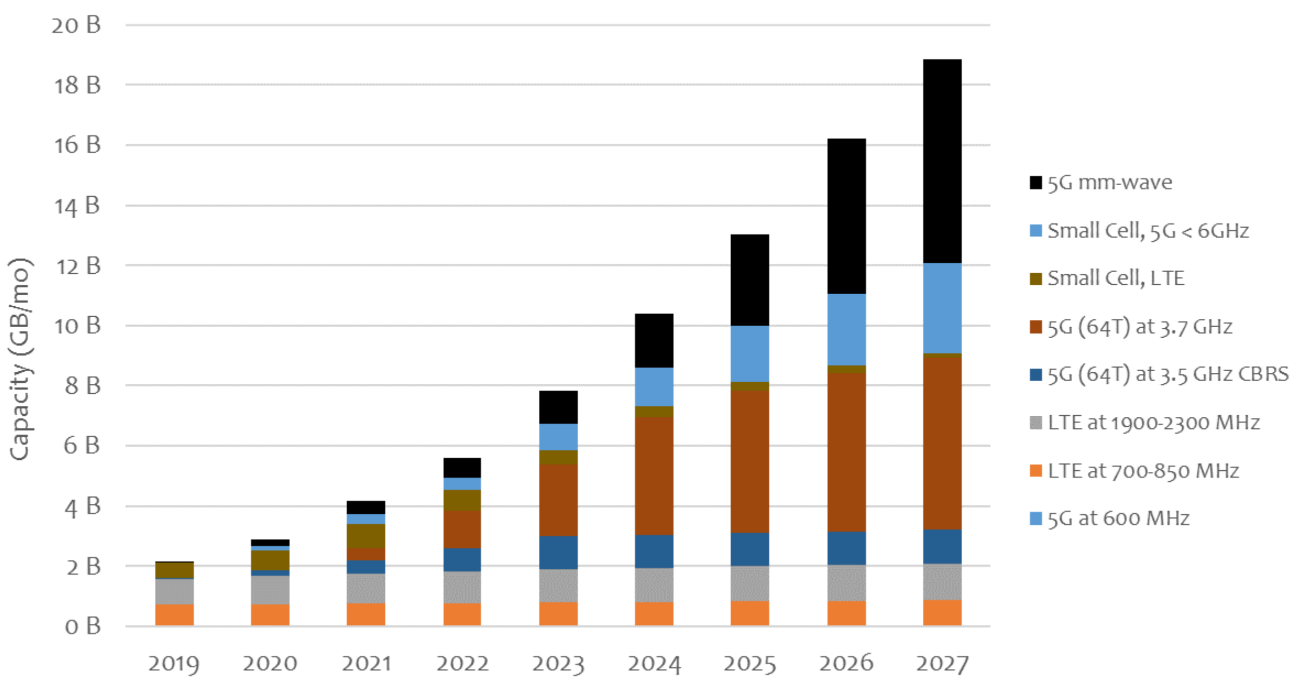

Figure 2 Capacity analysis of a nationwide US mobile network

Source: Mobile Experts

The key point in capacity modeling of US networks is that, due to a shortage of spectrum at 3-5 GHz, AT&T and Verizon will be forced to use mm-wave spectrum to keep up with demand. In urban locations, these two operators are likely to run out of capacity below 6 GHz in the 2023 timeframe.

T-Mobile and Sprint, on the other hand, have access to a wide block of spectrum at 2.5 GHz, so in the case of "New T-Mobile" we don't expect a dire need for mm-wave capacity until about 2027. Even then, T-Mobile and Sprint will need to increase their combined market share in order to exceed the peak capacity of their combined spectrum.

Outside of the USA, we anticipate deployment of mm-wave capacity in dense pockets of Seoul during the 2020-2024 timeframe. It's possible that Japanese or Chinese operators could also step up to the mm-wave bands in 2023-2024, but today there are no indications of large-scale plans in these other Asian markets.

Distractions that don't really drive this market

In the media, Virtual Reality and Movie Downloads are often cited as applications to drive gigabit speed requirements. There are multiple counterpoints to these fantasies:

- Virtual Reality can require up to 500 Mbps for a full, immersive, low latency experience. However, we do not expect this market to jump directly to the outdoor mobile world. It's far more likely that VR will develop as a short-range system first, in homes, stadiums, or other entertainment locations. Every other application for mobile devices has started as a wired application first, and we expect VR to be no different. We simply cannot imagine the full VR goggles on people that are moving around outdoors.
- Augmented Reality requires much lower bandwidth because the images displayed occupy a much smaller portion of the user's field of view. We expect Augmented Reality applications to begin at data speeds in the range of 10 Mbps or less. Latency for most applications will not be critical.
- File Synchronization is a possible use case. Dropbox, photo sharing services, and other cloud services can exchange huge amounts of data between client devices and the Cloud. The usage of these services is growing, so this is a potential source of data demand at high speed. Very few customers are currently concerned about speed in their file-sync programs today, so while this application can drive huge volume, we don't think speed or latency are necessarily the key factors.
- Movie Downloads could be another source of 5G demand. Downloading a 5 GB HD movie can require several minutes, and in this case the user is left waiting for the download to finish. Currently, streaming services constitute the majority of the market. It's possible that in the future, downloads will become a major driver but current trends are not pointing in that direction. As a reality check, keep in mind that WiGig (60 GHz super-broadband) has been available for over ten years for this application and has never been adopted.

Overall, we see some potential for future growth in data demand, but we don't see strong evidence that end users will use a 2 Gbps link. Our conclusion is that faster speed is NOT very important in 5G.

Instead, higher capacity is actually the key. Millions of users at 40 Mbps create a lot of demand, and 5G is necessary for capacity even if none of them use a 2 Gbps link.

Market Challenges

The main challenges for mobile operators will be technical in nature:

- Propagation at 24-40 GHz involves a high degree of attenuation, subject to variability with rain, foliage, and other factors. Penetration of walls is pitifully weak, so mobile coverage from each gNodeB will be small.
- Narrow beams can be used to extend range, but then users can easily be lost with multipath variations. In this way, the mm-wave network is not a reliable link for mobile control signaling.
- Handsets and other hand-held client devices face challenges because the user's hands will block the antennas. The human hand can have 50 dB attenuation or even higher, so this can effectively block the mm-wave service altogether.

On the business side, operators will be very selective about which neighborhoods are covered by 5G mm-wave sites. In general, they will choose macro sectors with a traffic density higher than about 0.1 Gbps/km2/MHz, where small cells have already been deployed and additional capacity is still needed.

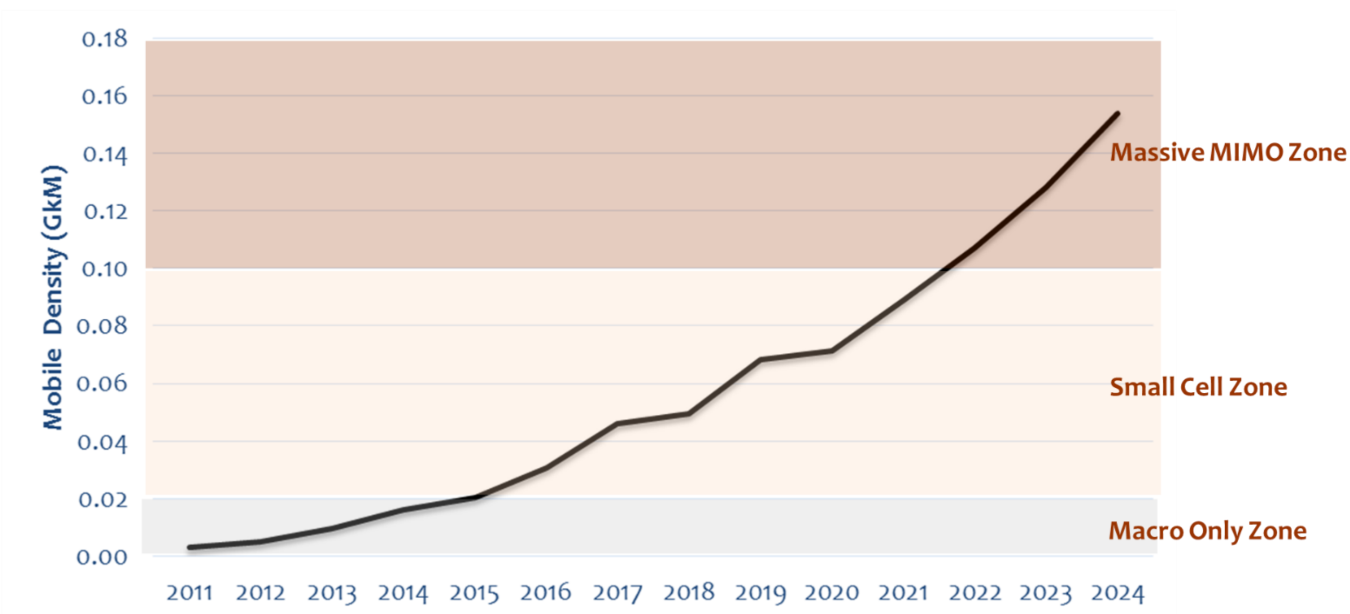

Figure 3 Tracking mobile traffic density in a major US city

Source: Mobile Experts

The main reason that operators will only deploy above about 0.1 GkM: at lower levels, the mm-wave capacity will not be utilized enough to pay for the network costs.

3 5G Technology

The evolution from 2G to 3G and 4G was a sequence of upgrades to the air interface, with the primary focus on the waveform used to digitize information for wireless transfer. Each generation brought higher spectral efficiency through better ways to package the data in the RF channel.

But 5G is different. In 5G NR, we use OFDM techniques that are very similar to 4G, with some upgrades that increase efficiency by 10% or so. From an air interface point of view, 5G is not really much better than 4G. The difference comes in the spectrum and the use of spatial techniques.

First, the point on spectrum is simple. With 5G, operators are tapping into wider blocks of spectrum. At 2.5 through 4.9 GHz, several operators are targeting 100 MHz blocks or wider, which gives them a significant boost in capacity.

Secondly, most 5G networks will use Massive MIMO to increase spectral efficiency through better re-use of spectrum in the spatial domain. Instead of three fixed sectors per base station site, with massive MIMO each sector can support multiple beams. When each beam shares the same spectrum, the site is effectively re-using spectrum better. Put another way, it can be the equivalent of arranging the antennas for twelve sectors per site instead of three.

Overall 5G Architecture

The term "5G" refers to the waveform in the mobile market, but there are many other technologies that go along with the new waveform:

- Virtualization: The core networks and baseband processing are quickly moving toward the use of commodity servers. Standardized hardware will allow for greater scalability of the network and lower cost.
- New Fronthaul Interfaces: Real-time baseband processing of the PHY and lower MAC layers will take place in the Radio Unit (RU), instead of its previous centralization. This change has the impact of reducing the bandwidth required on the fronthaul link, so that each fiber strand can handle more over-the-air traffic. (We use the term RU to indicate a new radio unit which includes these baseband functions, where a Remote Radio Head (RRH) in the LTE market typically worked on a CPRI interface with no baseband processing in the RRH.)
- Mobile Edge Computing: As the core network and baseband functions are virtualized, the network can be more flexible to place computing resources closer to the end user.
- Massive MIMO: This antenna technique has been applied to LTE as well, and in fact Massive MIMO is independent of the waveform that is used in the radio channel. Generally, Massive MIMO is considered part of 5G because most of the capacity benefits of next-generation deployments will come from Massive MIMO.

All of these architectural changes will become important in the adoption of wideband mm-wave radios. We cover each of these technologies more thoroughly in other reports, so here we focus our comments on their impact to the 5G mm-wave network.

First of all, by virtualizing the baseband processing, the operators will enjoy a greater level of flexibility in the network. Baseband elements and core network functions can be moved to different locations, because the standard servers at multiple locations will be suitable to run the software.

This is a major improvement over the previous architecture with dedicated hardware for each function. The impact for 5G mm-wave networks will be a reduction in cost per GB. The use of the mm-wave bands can bring down the cost per GB in the radio dramatically, but if the cost per GB remained high in the baseband processing or core network areas, the radio upgrade would be pointless.

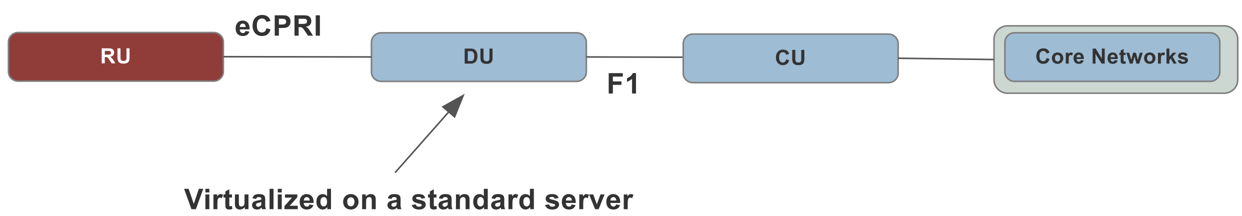

Figure 4 The Virtualized Network Architecture

Source: Mobile Experts

Secondly, the architecture for CPRI fronthaul was reaching its limits. Developed in 2002-2004 as a way to disaggregate the Remote Radio Head and the Baseband Unit (BBU), the CPRI architecture uses a serialized I/Q data interface. Serialized data can be fine for 3G or LTE signals that have limited bandwidth, but in the case of a 5G mm-wave link the bandwidth requirement for a serialized I/Q stream would be ridiculous at hundreds of Gbps. This would stretch the state of the art in fiberoptic transceivers, and it's not necessary. By separating the real-time baseband processing in the PHY and lower MAC layers, the system engineer can dramatically reduce the bandwidth requirement in the fronthaul link. A 5G mm-wave gNodeB site with 3 sectors can use 'midhaul' of roughly 20 Gbps, whereas CPRI would have required as much as 150 Gbps.

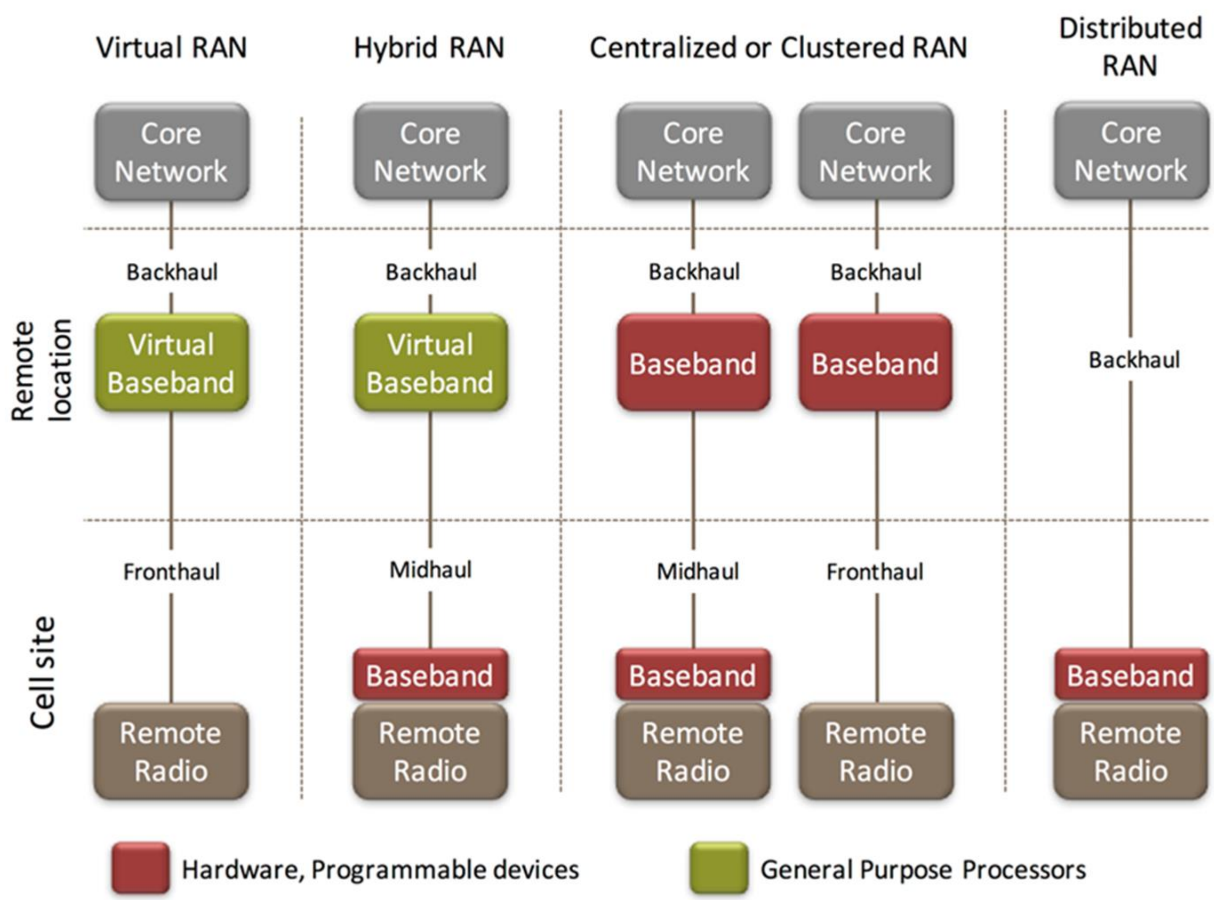

Figure 5 Virtualizing the Network and Shifting to 'Hybrid RAN' for lower transport cost

Source: Mobile Experts

Third, Mobile Edge Computing will be useful for 5G mm-wave services. In the world of streaming video, the long-haul cost for transporting each video to an end user individually can be prohibitive. As an example, a sporting event may be streamed by millions of people living in Chicago. By staging the video in a Content Delivery Network (CDN) in Chicago, the operator only pays the long-haul cost for the video once. The impact from a technical point of view is minor in the case of videos, but at a business level the cost savings can be serious.

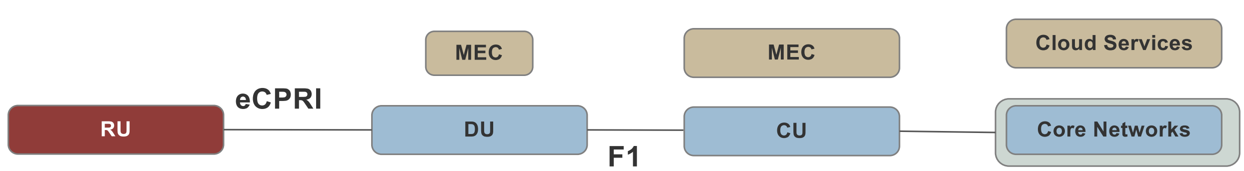

Figure 6 Adding Edge Computing to local and regional data centers to reduce long-haul cost

Source: Mobile Experts

Massive MIMO—clearing up some confusing terminology

From a capacity and cost-per-bit point of view, Massive MIMO is clearly the most important technology upgrade to mobile networks. Changing from a simpler 4T4R radio to 64T64R can increase spectral efficiency from 2 bps/Hz to more than 6 bps/Hz.

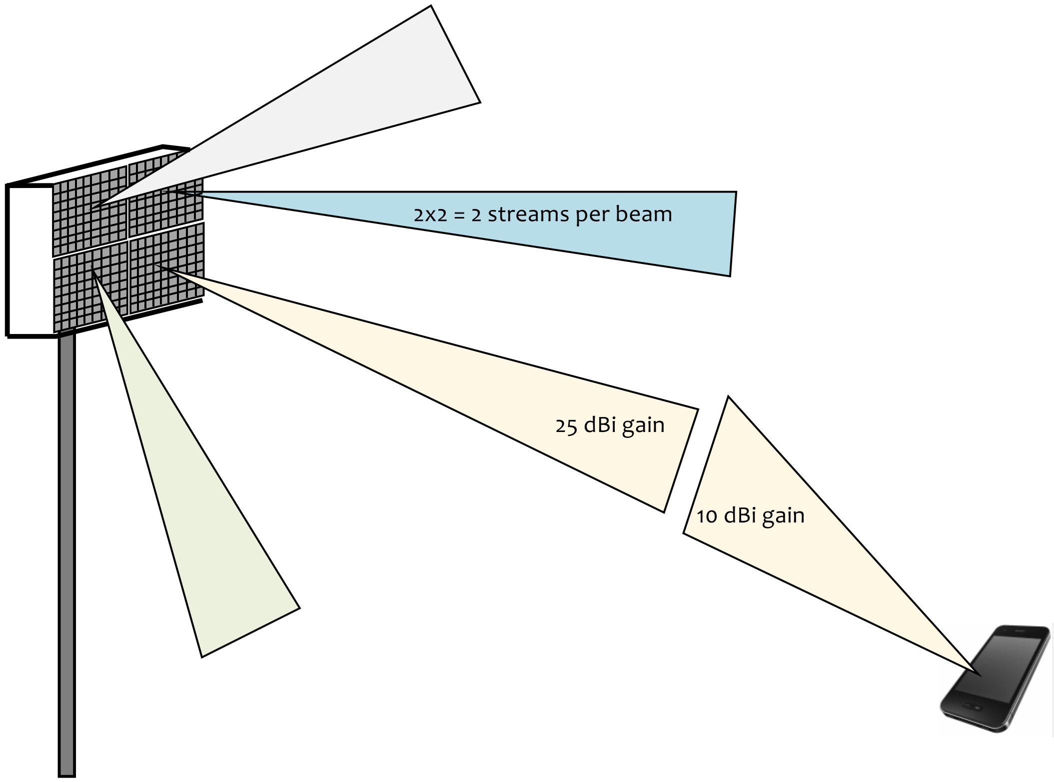

Figure 7   Diagram illustrating one sector with four beams and eight streams

Source: Mobile Experts

Massive MIMO is defined as a configuration with an active antenna array, using 16 transceivers per sector or higher. The Active Antenna System is often called an AAS.

Each antenna array can be built using multiple panels. Four 64T64R panels can be mounted together to create a 256T256R AAS. At mm-wave frequencies, the number of panels is limited more by cost and power/heat dissipation than by size limitations.

In some configurations, each panel is responsible for a single beam. This is not necessarily the case, as it's very possible to reconfigure the software for multiple beams per panel. In the mm-wave bands, using 64 antenna elements to transmit a signal results in about 25 dBi of antenna gain, which is an important part of compensating for the poor propagation of the mm-wave energy. Some initial products use a 64T64R panel for a single beam, because that is a convenient modular size…in this way, three panels can be used for three beams and a fourth panel can be added for even more capacity.

Each beam can have multiple streams. For example, within a beam, 2x2 MIMO can be employed so that a system with four beams uses eight spatial streams.

On the client device, the mm-wave system will utilize multiple sub-arrays in order to make three-dimensional beamforming possible. A typical configuration could be three or four sub-arrays on a smartphone, with each sub-array consisting of four antenna elements. This translates into 12-16 active radios and power amplifiers on the handset.

At millimeter wave frequencies, the number of antenna elements depends on the use of polarization. Often, a 64T radio will actually have 128 antenna elements because two polarizations can apply for each. Mobile Experts refers to the number of transmitter outputs (power amplifiers) as our basic unit of measurement, independent of the use of polarization.

How 5G mm-wave can work without continuous links

Many engineers object, saying that 5G mm-wave bands are not suitable for mobile services. It's quite true that a stand-alone 5G mm-wave service would be problematic. The narrow beams and poor signal propagation would make high-speed handovers very difficult.

For that reason, 5G mm-wave networks will be implemented as "Non-Stand Alone" (NSA) networks, in which the LTE control signals will maintain a continuous link, and the 5G layer can be added when it's available. Non-Stand Alone also refers to the use of the LTE core network, and over time as the core network migrates to 5G we do expect to see some Stand Alone (SA) 5G networks. However, only 5G networks below 5 GHz are likely to use this approach.

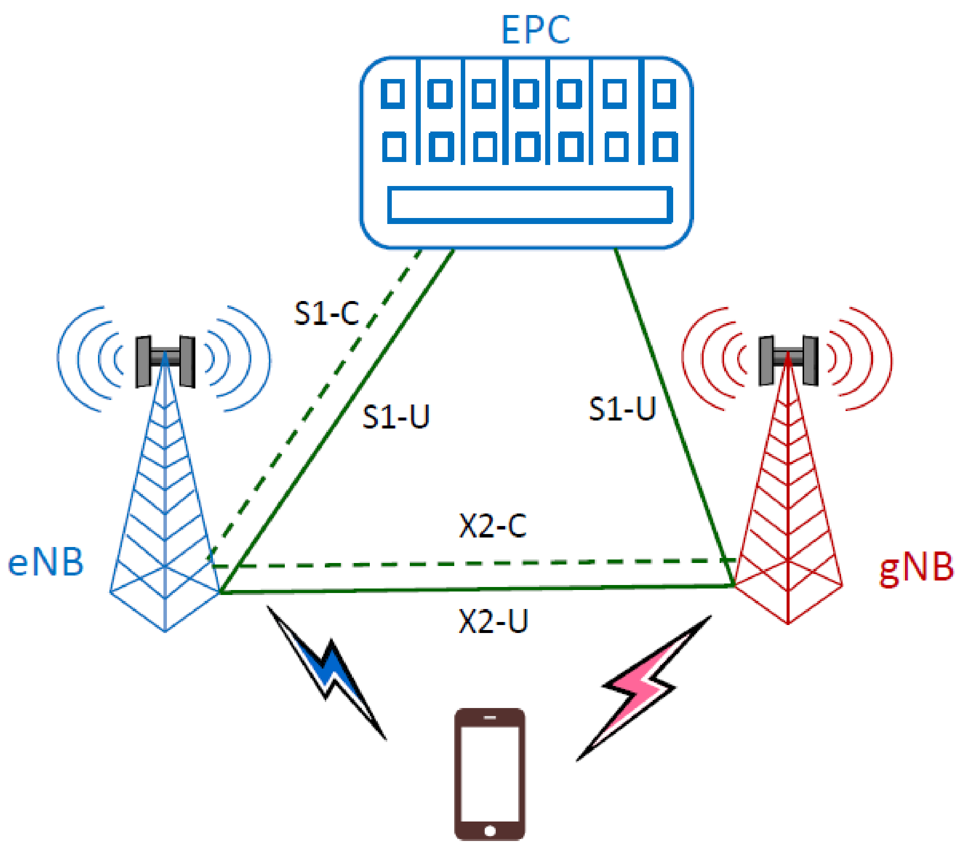

Figure 8 Dual Connectivity using Option 3 (LTE and 5G NR with EPC)

Source: 3G4G

High Level Architecture Decisions

The operators involved in 3GPP have agreed to focus on a few variations of the high level network architecture, to move these options along most quickly. Here's a quick summary of some key decisions which focus current 5G NR development on specific architectural choices….keep in mind that these decisions can be altered later, as new options will be added to the 3GPP standards over time.

- The control plane and user plane will be independent. This means that control signals can come from a different eNodeB than the data payload, or can be on a different band.
- The Central Unit and Digital unit will be split, so baseband processing functions and some core network functions can be independent. The impact of this split is not clear at a business level because there's no consensus on how this split/interface will work, so we don't expect an interoperable interface which would allow for competition to enter here.

- The "Option 3" and "Option 2" combinations of radio networks and core networks are the focus for the near term, as 5G core networks are not ready. Eventually we expect migration to Options 5 and 7, using the 5G core network.

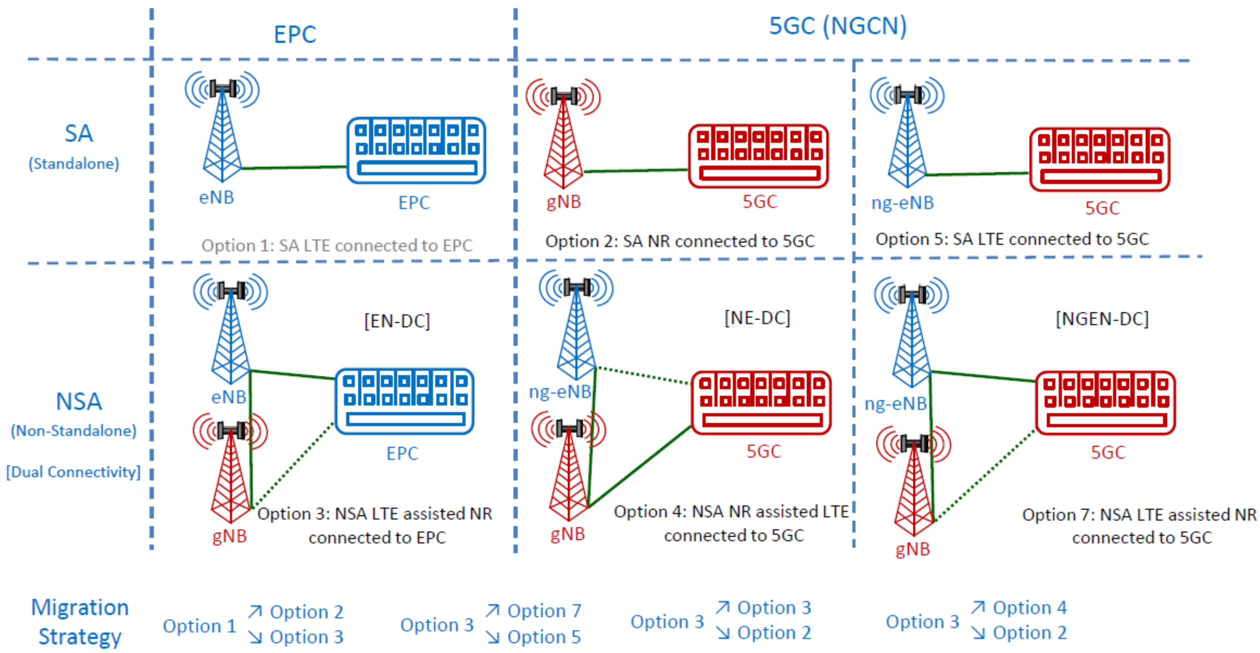

Figure 9 Mobile Network High-Level Architecture Evolution

Source: 3G4G

Standards Status

Release 15 of the 3GPP standards is wrapping up, with the first specifications frozen in early 2018 and the "late drop" specifications frozen in 1Q2019. The "late drop" ASN.1 documents should be released by roughly May 2019. The committees are well on their way to Release 16, which will include a "Phase 2" of radio specifications that focus on the efficiency of 5G as well as expansion into new business areas.

- Efficiency items include 5G SON, MIMO enhancements, power consumption improvements, etc.
- Expansion items include Vehicle-to-Vehicle, Vehicle-to-Infrastructure, Industrial IOT, URLLC, and Unlicensed operation.

Release 16 work items should be completed by December 2019, with ASN.1 freeze in March 2020.

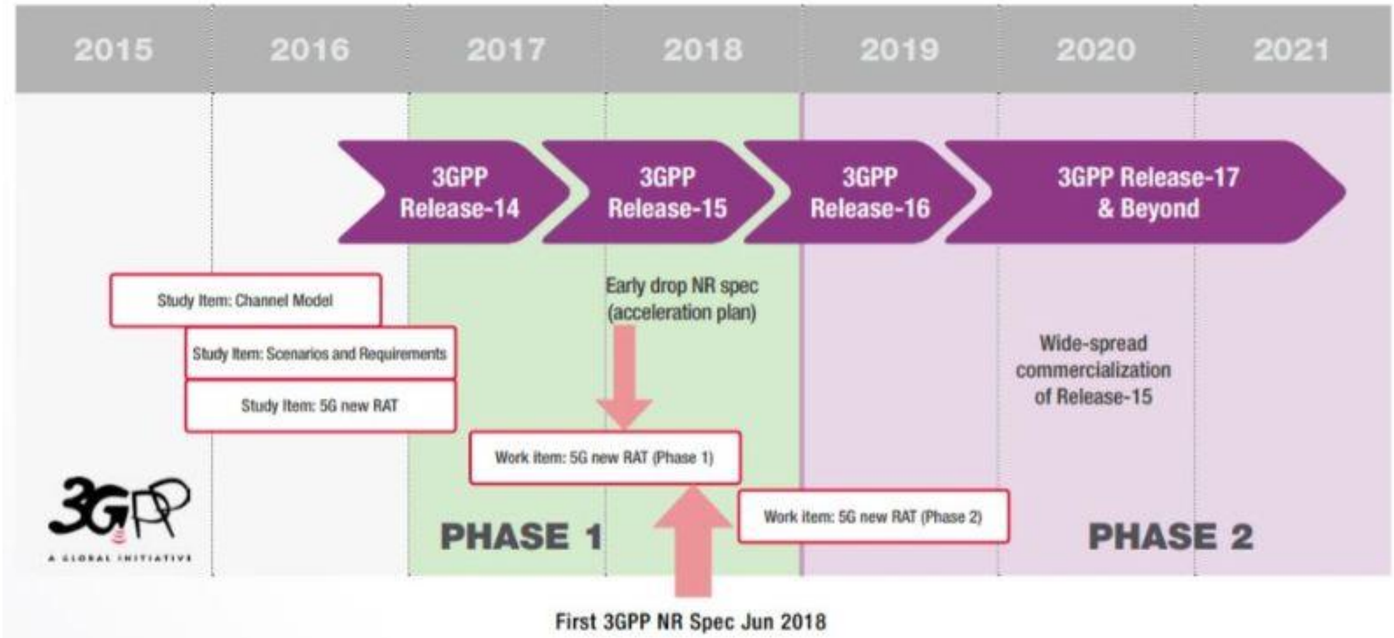

Figure 10   3GPP RAN Timeline for 5G NR standards

Source: Keysight/3GPP

4 SPECTRUM

As always in mobile networks, spectrum is a key issue for 5G mm-wave systems. Nobody would call mm-wave spectrum their "first choice" for 5G, but some operators are forced to use mm-wave bands because all other bands are already occupied. We focus our analysis on the USA and South Korea, because these two countries have enough traffic to overwhelm the capacity of bands below 6 GHz. Other countries will also reach this level, after making use of 5G bands below 6 GHz.

United States

In the USA, mm-wave spectrum is a key focal point for 5G because all other new frequency bands below 6 GHz are occupied with other users. Some bands on not used efficiently, and the US Federal Communications Commission (FCC) is working on ideas to consolidate some bands, or share bands to increase availability. As one example, the CBRS band from 3.55 GHz to 3.7 GHz will be opened up over the next year for LTE and 5G services, but broken up into 10 MHz licenses that will be sold on a county-by-county level. The narrow bandwidth and small geographic size makes this band useful for enterprises but less useful for nationwide 5G broadband. Similarly, the US government may consolidate some satellite users between 3.7 and 4.2 GHz, to clear about 100-200 MHz of spectrum for mobile use. If this happens, then one or two operators could benefit from a wider block of 5G spectrum that's capable of long range. Any plans in the 3.7 to 4.2 GHz band will need to wait at least 2-3 more years because the existing satellite users must be convinced to move, and the political fight will be intense.

Sprint is the only US carrier with adequate spectrum for a broadband 5G network. The merger of T-Mobile and Sprint is likely to create a company with the spectrum assets and the financial muscle to implement a solid nationwide 5G network. Another option is the DISH Network spectrum, which consists of smallish blocks of spectrum scattered between 700 MHz and 2300 MHz. In aggregate, DISH has about 95 MHz of spectrum, but the fragmented nature of the bands makes it difficult to use for 5G broadband.

Because the options below 6 GHz are weak, Verizon started several years ago to quietly acquire spectrum in the 28 GHz and 39 GHz bands. Verizon acquired XO Communications, which included some interesting fiber assets but also a treasure trove of 180 billion MHz-POPs of spectrum. Verizon quickly moved on to acquire Straightpath Communications, which held about 175 billion MHz-POPs of spectrum at 28 GHz and 39 GHz. Altogether, these deals put Verizon firmly in the lead with more than half of all possible 28 GHz spectrum and 39% of all spectrum at 39 GHz. AT&T holds 27% of the 39 GHz band through its acquisition of FiberTower, but very little other mm-wave spectrum. In terms of coverage for key cities, both AT&T and Verizon have 300+ MHz of spectrum in many of the top 20 cities in the USA.

Frequency Band	3GPP Designation	Status
24.25-27.5 GHz	n258	Global band
24.25-24.45 and 24.75-25.25 GHz	None	USA band to be auctioned
26.5-29.5 GHz	n257	Global band
37.0-40.0 GHz	n260	Global band
27.5-28.35 GHz	n261	USA band

Auctions are the next step. The FCC recently completed their first auction at 28 GHz (27.5 to 28.35 GHz), selling almost 3,000 licenses for $702 M. The 24 GHz band will be auctioned next, with about 2.900 licenses between 24.25-24.45 GHz and 24.75-25.25 GHz bands. The 37, 39, and 47 GHz bands will first go through an 'incentive auction', which allows the industry to pay incumbent users to give up their licenses. Overall, we expect more than 3 GHz of new spectrum to become available for long-term use in the mobile market through these bands.

South Korea

In the South Korean market, each operator will have 100 MHz of spectrum at 3.5 GHz, so the immediate pressure for capacity will be satisfied by macro network upgrades in the new C-band spectrum. However, traffic demand growth remains high in Korea, and we expect the operators to utilize 28 GHz mm-wave spectrum in key urban pockets starting in roughly 2021 or 2022.

SKT, LGU+, and KT each have 800 MHz of spectrum in Band n257. Notably, the Korean auction resulted in licenses for only 5 years, but the $600 million cost is high compared with the recent auction in the USA.

- KT: 26.5-27.3 GHz
- LGU+: 27.3-28.1 GHz
- SKT: 28.1 – 28.9 GHz

Other Countries: China, Japan, Europe, etc

Other countries have intentions but not solid licenses or plans.

- In China, the 24.75 – 27.5 GHz and 37-42.5 GHz bands are under consideration. Our prediction is for China to license mm-wave spectrum in roughly the 2023 timeframe.
- In Japan, 27.5 to 29.5 GHz is confirmed as a band for mobile use. Auction plans are not fixed yet, but we anticipate an auction process resulting in licenses sometime during 2020.
- European countries will use blocks of spectrum in the 24.25-27.5 GHz band, with possibilities in the 40-43 GHz band. We expect the timing to be quick in a few countries such as Finland, Estonia, and Sweden but most of Europe will be delayed to roughly 2025.
- In the Middle East, a few countries will follow European bands and move quickly toward mm-wave. Dubai, Saudi Arabia, and a few others will have pockets of deployment in the 2023 timeframe.

Licensed and Unlicensed bands above 20 GHz

This report is pretty focused on 24 GHz, 28 GHz, and 39 GHz bands, but in fact several other bands are possible worldwide. Licensed bands are the most feasible for wide-area system implementation, but unlicensed bands are also possible in the 60 GHz band. In short, there is a lot of room for growth in capacity with about 15-20 GHz of possible spectrum available in many countries.

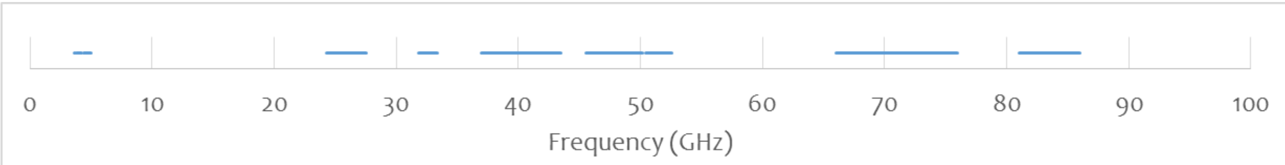

Figure 11. Spectrum blocks considered at WRC-15 for 5G

Source: WRC-15

60 GHz: The unlicensed band at 60 GHz is tempting, with a wide block of spectrum that is free. The US Government made a ruling that this use of the 60 GHz band would be authorized for mobile services, but other countries have been silent on this issue so far. The supply chain is not convinced, as we have not seen a strong R&D push in this direction.

5 INFRASTRUCTURE RADIO IMPLEMENTATION

The early implementation of 5G mm-wave networks will use a Non-Stand Alone (NSA) architecture to benefit from the coverage and control channels of the LTE network. The radios will be deployed on rooftops, streetlights and other "street furniture" roughly 10-20 meters above the ground, and hardware will be chosen with the highest possible EIRP for long-range coverage given a fixed power/heat budget.

Over time, 5G networks below 6 GHz will transition to Stand Alone (SA) architectures, but mm-wave networks are unlikely to follow this path, despite the benefits of completely stand alone operation. The completeness of mm-wave coverage simply will not be good enough, especially in the uplink, for mobility in this environment. However, fixed-wireless operation could be possible in SA mode for any operators that have ongoing FWA deployment.

In the radio, there are a few key features to highlight:

The 5G Waveform and Massive MIMO

The 5G OFDM waveform itself is not an earth-shaking improvement over LTE. Lab testing and field trials indicate that the improved CP-OFDM waveform provides about 10% capacity benefit, compared with a similar LTE bandwidth. The improvement, then, lies in the lower latency of the frame structure and potential for higher reliability.

While the waveform is reaching a physical limit in its spectral efficiency, 5G mm-wave networks will make heavy use of Massive MIMO to increase *spatial efficiency*. In other words, each data stream may still carry roughly 1-2 bps/Hz, but using Massive MIMO, we can dramatically increase the numbers of data streams for each gNodeB site.

In the millimeter-wave bands, the level of efficiency performance of the electronics can be seen directly in the size of the enclosure and the output power. Here's a direct comparison based on vendor statements and FCC filings:

Massive MIMO Array Configuration

The terminology associated with large Massive MIMO arrays can be confusing. The number of antenna elements is commonly discussed, but the more important metrics for comparison are related to the output power of the array in terms of Effective Isotropic Radiated Power (EIRP), as well as the number of beams and streams supported by the array.

… Antenna Polarizations

Two basic antenna configurations can be used for a TDD-based Massive MIMO system. In one simple configuration, the transmit antenna elements are separated from the receiving antenna elements. This provides some isolation between transmit and receiver without T/R switch losses, allowing for two MIMO streams to utilize the two polarizations available in the array.

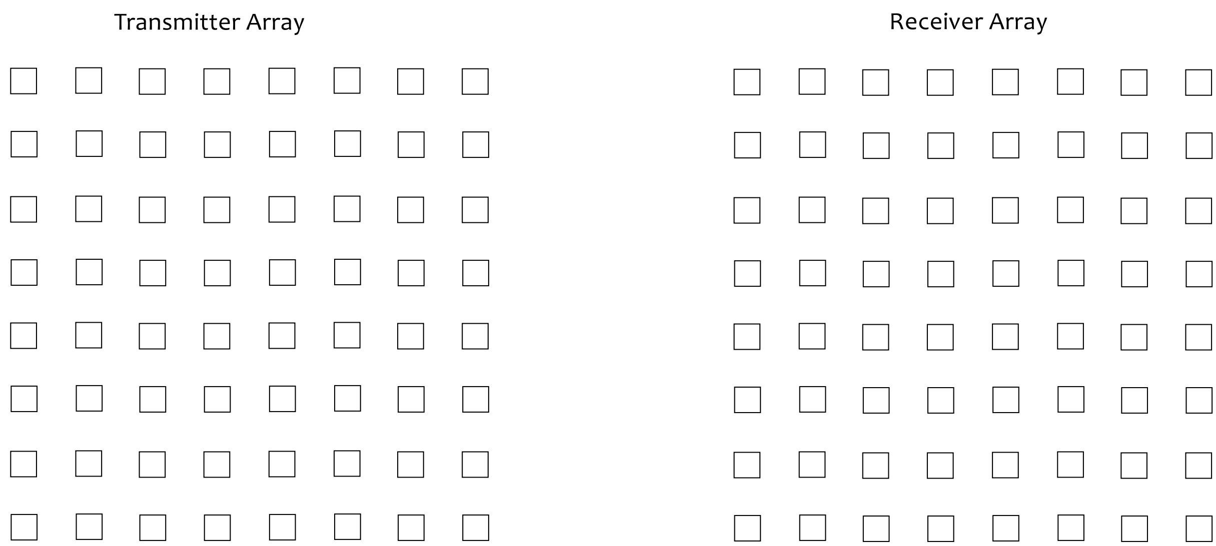

Figure 12. Dual Arrays without a need for T/R switch

Source: Mobile Experts

All of the major OEMs have now migrated to a dual-polarization arrangement, where each patch antenna uses orthogonal transmit and receive modes. This approach saves space over the previous concept of separate arrays for transmitter and receiver, while still allowing for two MIMO streams to be transmitted and received on a single array A T/R switch is used behind each antenna element to route the transmitter or receiver.

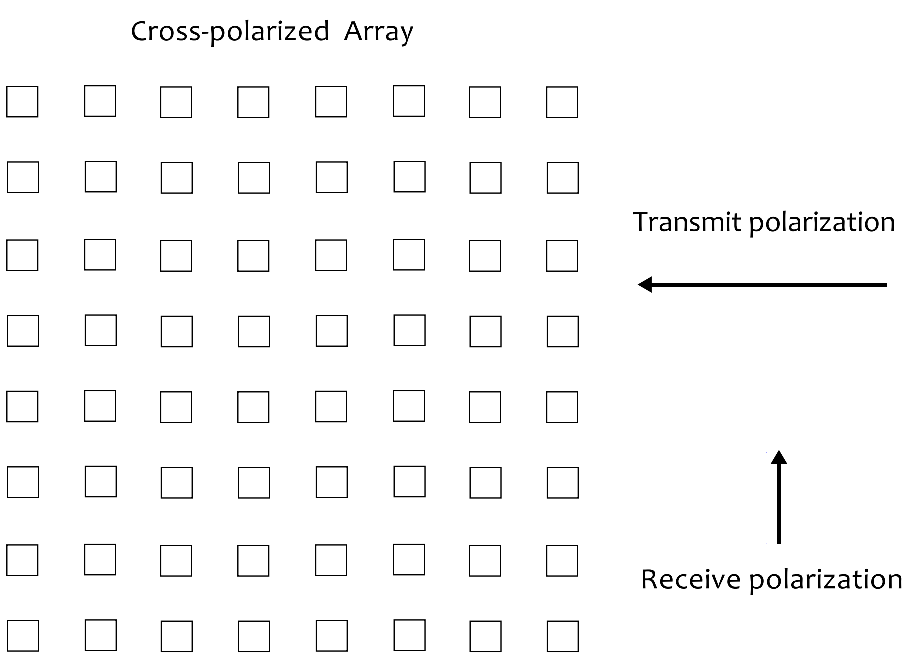

Figure 13. Cross-polarized antenna array

Source: Mobile Experts

… Number of Beams

The number of beams that are used can be defined by software, up to a limit. In general, higher numbers of antenna elements will allow for sharper definition between multiple antenna beams. A panel of 8 antenna elements in the horizontal plane creates a beam with 12 degrees of beamwidth, but increasing the number of elements to 24 reduces beamwidth to only 4 degrees. The isolation between beams also improves with higher numbers of elements, increasing spectral efficiency.

The number of beams that are practically realizable in an array will be limited to ¼ the number of antenna elements, because at least four antenna elements are required to form and steer a beam in both horizontal and vertical dimensions.

The number of beams is directly related to the spectral efficiency and capacity of the site. With higher numbers of high-gain beams, an operator can boost spectral efficiency from 1-2 bps/Hz to much higher values. For millimeter-wave systems with 256-1024 antenna elements, 6-8 bps/Hz has been achieved in field trials.

… Number of Streams

In all 5G mm-wave systems deployed so far, each beam carries 2x2 MIMO for the individual users. This means that two I/Q data streams are fed to the section of the array that carries each beam. (transmitted on separate polarizations for orthogonality). This configuration is also software definable, assuming that the level of baseband processing capacity and the up/downconverters can handle a flexible configuration of data streams. For now, the market uses two spatial streams per massive MIMO beam. We expect to track changes in this configuration over the long-term development of the market.

… Number of Amplifiers

The radio configuration for mm-wave arrays may evolve very differently than similar arrays in lower bands. In the mm-wave array, the low efficiency of power amplifiers can be a severely limiting factor: too much heat is generated in the PA, resulting in overheating in a passively cooled radio head. The practical result is that output power must be reduced, which in turn reduces the range of the radio link. Mobile operators can't make money on a mm-wave network unless they can achieve long range, so this factor is critical.

One solution to the problem is to increase the antenna gain, by using large numbers of antenna elements for each beam. Some products currently use between 64 and 256 elements to form antenna beams with 23-30 dBi gain. In this way, the conducted power of each PA can be reduced to less than 15 dBm, and the heat dissipation can be kept to a minimum.

Another approach could be to use the most efficient semiconductor process for mm-wave PA elements. Gallium Nitride power amplifiers can achieve 4 % power-added efficiency with high linearity (at 64QAM), compared with less than 1 % PAE for silicon-based alternatives. One possible approach to achieving high EIRP will involve the use of a few high-power GaN amplifiers instead of large numbers of low-power silicon amplifiers. In the GaN approach, a fanout structure can be used so that the GaN PA can feed multiple antenna elements and achieve both high power from the PA and high gain in the antenna.

In other words, the number of amplifiers in most products today is equal to the number of antenna elements. Using SOI and 512-1024 elements, mm-wave arrays can achieve linear EIRP of +60-63 dBm. In the future, with GaN amplifiers feeding a fanout to 512-1024 elements, we may see products with EIRP in the range of +70 dBm.

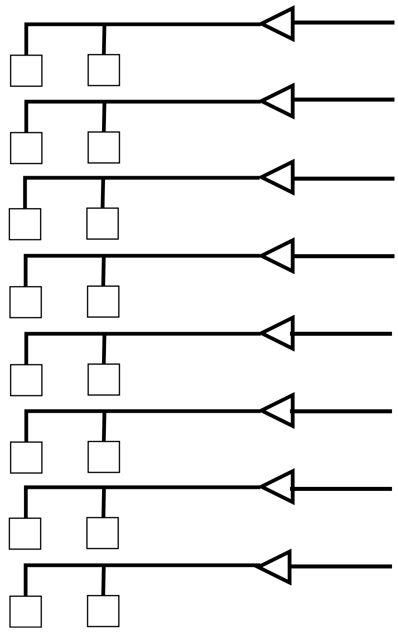

Figure 14. A simple fanout structure

Source: Mobile Experts

... Cooling approaches

The most obvious and fundamental challenge for 5G mm-wave radio hardware will be providing high RF power without active cooling. Some major OEMs have chosen to re-introduce active cooling into the radio unit, despite the clear desire of mobile operators to eliminate all moving parts in the radio. This illustrates how the heat of the radio electronics can be difficult to avoid.

Multiple vendors are using heat-pipes to distribute heat passively within the radio unit, and we photographed multiple different approaches to heat-sink fins at MWC 2019. The fundamental challenge is that, using passive techniques only, a small enclosure (roughly 250 x 250 x 10 mm) can only handle about 250 W of heat before the junction temperatures at the semiconductor level will start to cause failures.

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Figure 15. An example of deep heat-sink fins

Source: Mobile Experts (Samsung MWC demo)

… Panel Implementation

Some vendors refer to the number of antenna panels that are used in constructing the overall array. We interpret this term to mean that a large array (say 256 elements) consists of multiple physical panels with 64 elements per panel. By breaking up the large array into chunks, the system designer can create a more flexible product line, offering radio units with different configurations but re-using the same basic building block.

As one example, Nokia offers a mm-wave radio unit with four panels, facing each panel in different directions for 360 degree coverage. Samsung uses four panels with 256 elements each, for a total array of 1024 elements in one plane. We believe that innovation in the configuration and physical arrangement of these panels will be a source of differentiation in products for the next three years.

Vendor Comparison: Who has the best EIRP and Power Efficiency?

Vendor	Band	Antenna Configuration	RF Power (linear EIRP, 64QAM DL)	Dimensions	Estimated DC power dissipation
Nokia (Sept 2018 FCC filing)	28 GHz	Two 256 dual-pol antenna arrays Two 2x2 beam	+57 dBm per beam (2 beams)	522 x 304 x 161 mm. Optional fans listed in FCC report	Not disclosed publicly. Estimated 300 W
Nokia (MWC 2019)	39 GHz	Not disclosed publicly---covered under NDA			
Ericsson (Jan 2019 FCC filing)	39 GHz	192 dual-pol antenna elements/panel 4 panels 8 beams total	+51 dBm per beam +60 dBm total	600 x 303 x 110 mm	Not disclosed. Estimated 350 W
Ericsson (Oct 2018 FCC filing)	28 GHz (5GTF and 5G NR)	64 dual-pol antenna elements/panel 4 panels 8 beams total	+46 dBm per beam, +55dBm total	600x 300 x 90 mm	Not disclosed. Estimated 250 W
Ericsson AIR 5322 (expected product)	28 GHz	Unclear	+60dBm total	280 x 200 x 100 mm	300-400W (active cooling)
Ericsson AIR 1281	28 GHz	Unclear	+55 dBm total	280 x 200 x 100 mm	200-250W (passive cooling)
Samsung (Jan 2018 FCC report and MWC demo)	28 GHz	256 antenna elements per panel, 4 panels 2 beams, 2x2 MIMO each	+57 dBm per beam , (2 beams)	641x 256 x 122 mm	250-300W (passive cooling)
Samsung	39 GHz	256 dual-pol elements per panel, 2 panels One beam, 2x2 MIMO	+50 dBm	Approx 350 x 190 x 190 mm	200-250W (passive cooling)
Huawei	28 GHz	Estimated 1024 antenna elements	Unknown	Approx 700 x 300 x 150 mm	300W +

Figure 16. Comparison of various mm-wave RRH/AAS products for power, size, and efficiency

Source: Various vendors. Mobile

RF Implementation at 20-40 GHz

The RF components used at 28 GHz are very different than the approach taken in the 3-4 GHz range. Transitions and microstrip traces on a PCB are not going to work in the mm-wave range. For that reason, we expect to see much higher levels of integration.

…Physical Integration

The mm-wave radio will be highly integrated, with very close proximity for the antenna elements, filters, amplifiers, and data converters. In our view, the patch antenna elements that are most likely in the 28-40 GHz range must sit directly on top of buried waveguide filters and directly above the power amplifier/LNA components. Scaling this up to 256 elements or more will require a wafer-scale assembly or at minimum a set of multi-element components that fit together tightly.

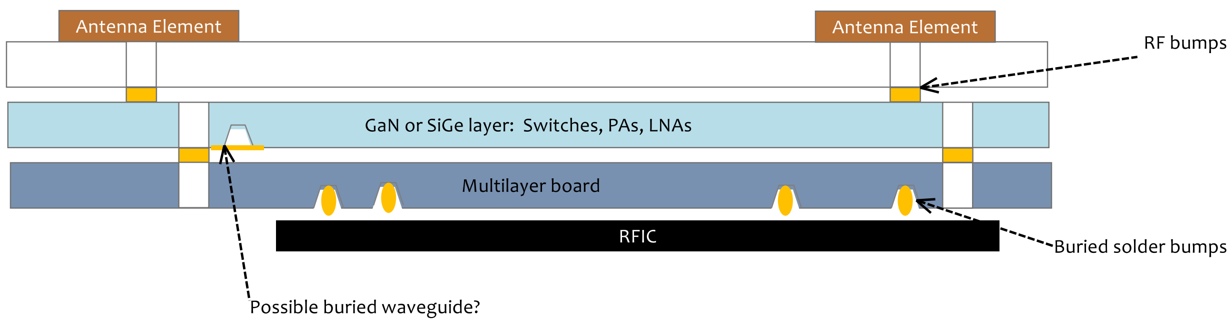

Figure 17. Possible construction of a high-power wafer scale assembly above 28 GHz

Source: Mobile Experts

Figure 18. Simpler construction for a silicon 5G radio/antenna array

Source: Mobile Experts

Companies that manufacture low temperature co-fired ceramics (LTCC) and RF glass are now lining up to manufacture mm-wave arrays at low cost. While last year's prototypes used costly and cumbersome techniques for packaging, we are starting to see technologies enter the market with a more straightforward and practical approach to integration.

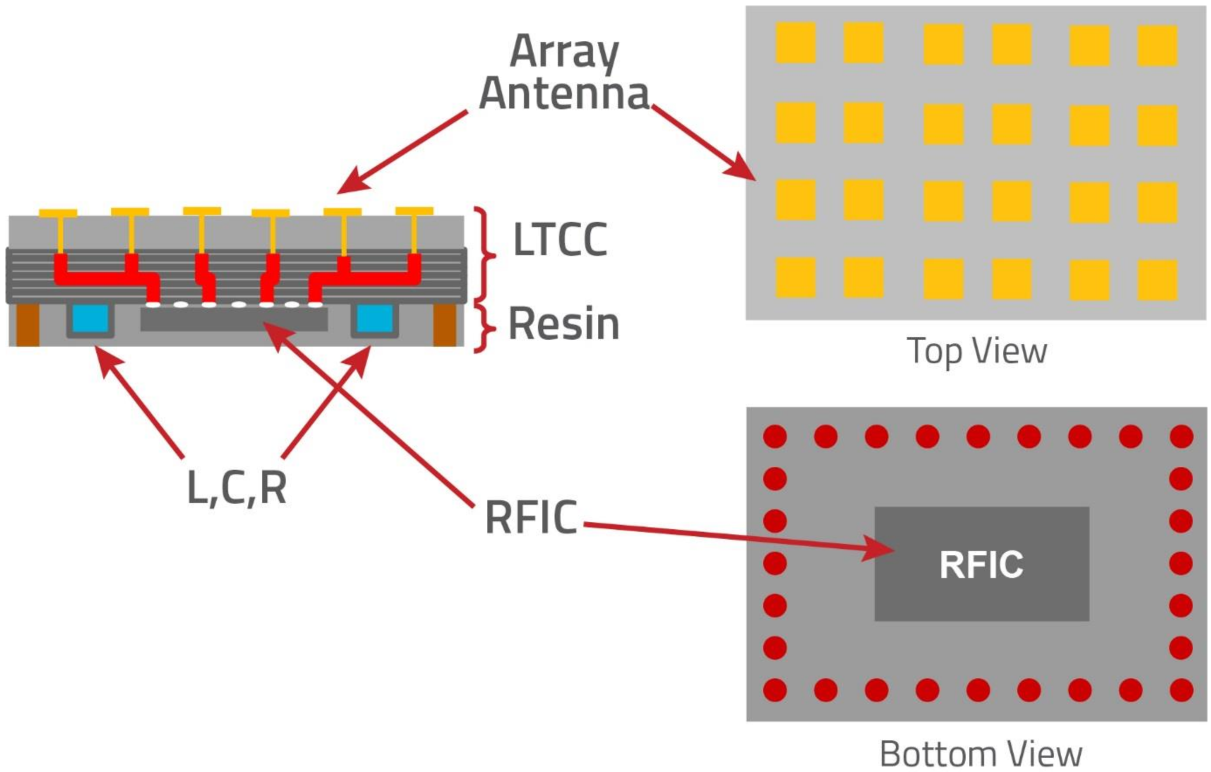

Figure 19. LTCC construction of an antenna array with RFICs and embedded passive devices

Source: pSemi

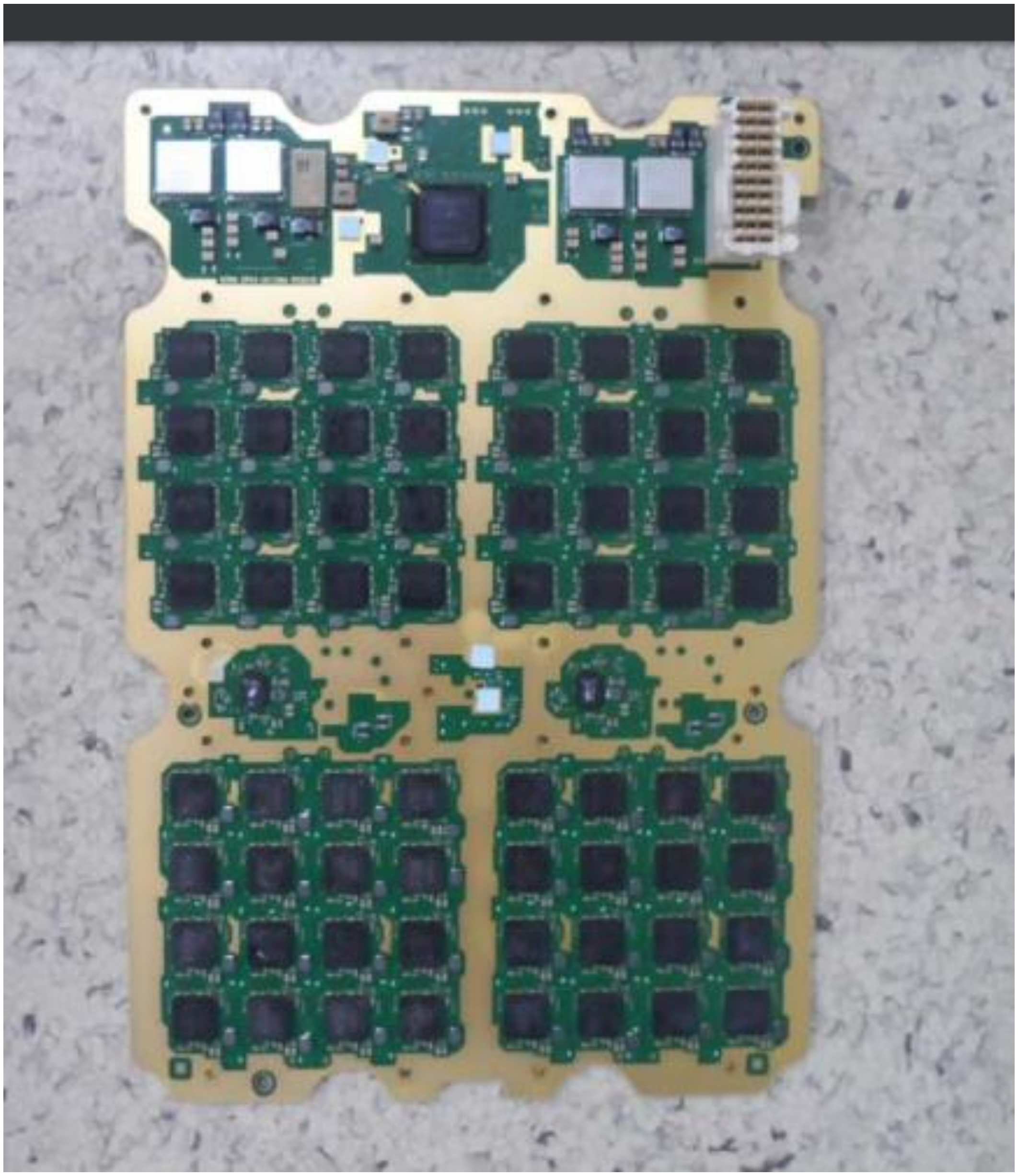

Figure 20. Internal photo from Samsung FCC filing—showing RFIC array

Source: FCC

…mm-wave Semiconductors: SOI, SiGe, or GaN?

In an RRH, efficiency of the power amplifier is the #1 biggest factor in determining how much RF power can be achieved and how much heat will be generated. The efficiency performance, ALCR performance, and total EIRP will be higher for GaN, and silicon (SOI or SiGe) have lower cost and easier integration with other functions.

Today, 5G systems integrators are currently focused on RF-SOI and SiGe to produce the beamforming and RF front end components in their arrays, and relying on high antenna gain to achieve the required EIRP. Ease of integration in the array is considered critical, as the OEMs want to use the minimum number of physical die to support a large array.

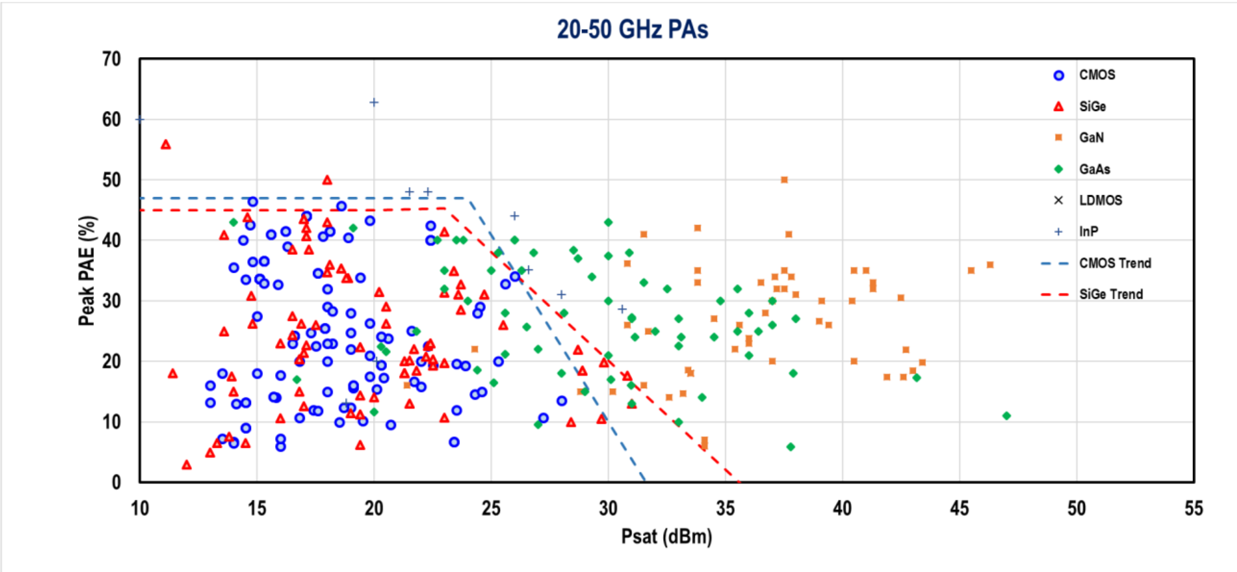

Figure 21. Comparison of CMOS, SiGe, GaAs, and GaN for mm-wave PA efficiency

Source: GA Tech

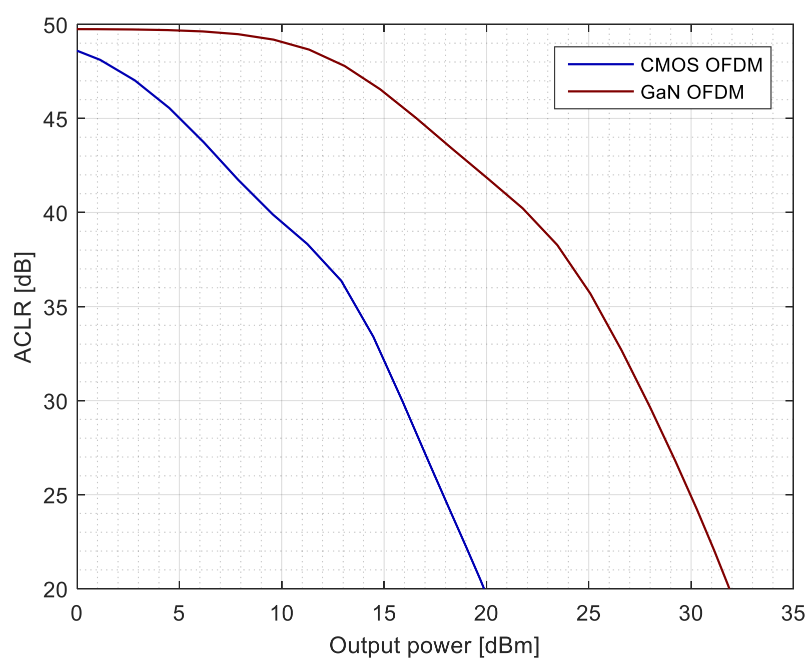

Figure 22. Comparison of GaN and SOI amplifiers for ACLR performance

Source: 3GPP RAN4

The two figures shown above summarize some of the key characteristics of GaN and SOI. Silicon can result in a cheaper, simpler module, but GaN has significant performance advantages in power capability, power-added efficiency, and linearity (ACLR) performance. With the same array size, GaN-based radios can achieve roughly 5-10 dB higher EIRP than SOI or SiGe… because the fundamental limitation in the system is heat dissipation.

In a practical sense, for a given requirement (such as +64 dBm linear EIRP), GaN can achieve the output power and linearity using much less power, typically with a much smaller array. The drawback of GaN comes in cost, level of integration, and manufacturing maturity. Based on recent demonstrations by major OEMs, we see minimum power consumption for SOI at about 150W to achieve +60 dBm, while GaN can achieve +64 dBm with only about 60 W of DC power, using much fewer amplifiers.

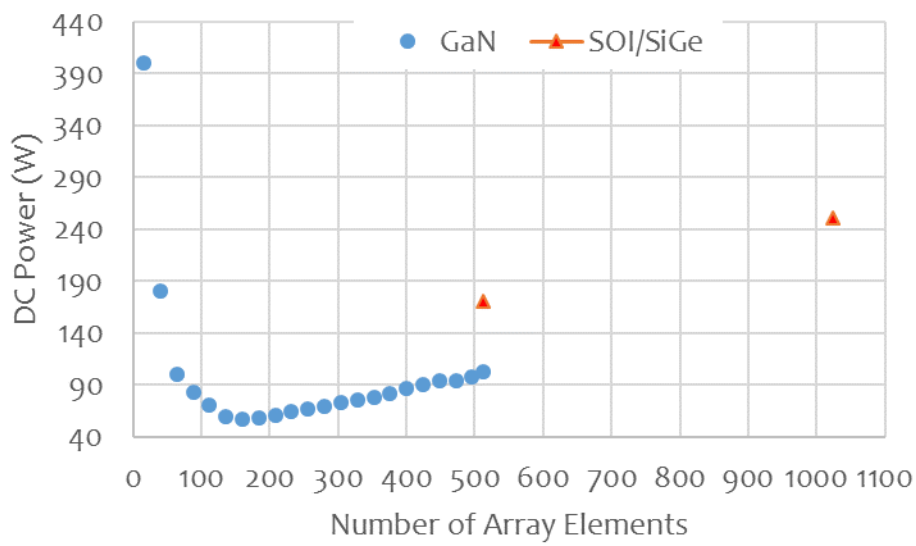

Figure 23. Amplifier power dissipation at 28 GHz using GaN (+64 dBm) and SOI/SiGe (+60 dBm)

Source: Qorvo,Mobile Experts. Assume 4% EVM.

Note: we see no demonstration in March 2019 of +60 dBm linear EIRP or higher with fewer than ~500 elements in SOI

Despite the PAE advantage of GaN, almost all of the initial 5G mm-wave array products use either RF-SOI or SiGe today. All of the OEMs view the cost and integration story to be compelling, because they can overcome limited EIRP through higher antenna gain. (Note that the higher antenna gain of bigger arrays also helps in terms of isolation between beams, resulting in higher spectral efficiency). Big arrays also allow for steering over a wide range in both vertical and horizontal dimensions. For 2019-2022 deployment of 5G mm-wave systems, we expect operators to deploy most arrays in dense urban locations, where vertical steering is important to cover tall buildings.

After 2022, we expect that mm-wave deployment may migrate to low-density urban locations where 2-3 story buildings are typical. If vertical beamsteering is no longer required, then a GaN approach with a fanout structure to achieve very high EIRP will be attractive.

In the end, we see SOI as a great choice for EIRP below +60 to +63 dBm per beam. Over time, we expect the capability of SOI to increase. In lab tests, SOI has reached +70 dBm linear EIRP (roughly 500 elements). As efficiency improvements are refined, we expect this level of performance to find its way into the radio unit.

… Beamforming

Radio engineers would like to achieve the ultimate in digital beamforming, with the DSP processing cores setting phase and amplitude for each element digitally. That's possible for narrow bands below 6 GHz, but for a 1 GHz bandwidth in the mm-wave range it's not a good tradeoff currently. The main drawback of the pure-digital beamforming technique is related to power consumption, as the correction of wideband steering for a large array can be very computation-intensive.

Above 24 GHz when side bands and wide steering angles are required, the power consumption of a digital beamformer can be prohibitive, so the major OEMs have considered analog beamforming. The analog approach has been used in radar systems for more than 60 years, and works great for narrowband signals. Analog beamforming allows for narrow beams using a lot of elements, but it lacks the flexibility of a digital beamformer.

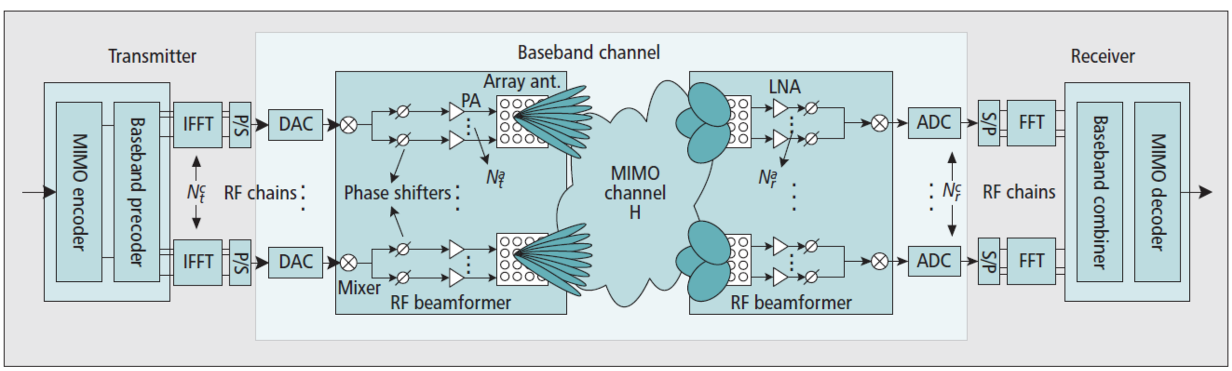

Figure 24. Hybrid Beamforming—end to end diagram

Source: Samsung

In particular, one issue with using a pure-analog approach is that analog beamforming only works well for narrowband signals. Wideband signals that are steered with simple analog phase shifters result in significant EVM errors, because the phase shift is only accurate for the center frequency, not the band edges.

To get the best combination of high gain (narrow beams) and the flexibility of digital processing, variations on the hybrid approach will be used by all major OEMs. In essence, the hybrid approach allows grouping of antenna elements to keep the number of RF paths to a minimum, while still allowing for a large number of elements and the corresponding narrow high-gain beam.

We expect hybrid beamforming to be used until Moore's Law can provide low-cost, low-power computing resources to handle very wide bands in a more practical way.

… ACLR, DPD, and Envelope Tracking

Now that 3GPP has settled down on CP-OFDM as a waveform for both uplink and downlink, we're starting to see the benefits and the issues related to it. Compared with other possible multiple access formats, the peak-to-average-power ratio (PAPR) of CP-OFDM is fairly high at about 10 dB. This will remain a little higher than LTE after accounting for crest factor reduction. Spectral efficiency is high, but the frame is contained so that it doesn't spread out in the time domain, making low latency possible. Out-of-band emissions are also high, but Qualcomm has proposed the use of WOLA (Windowing Overlap and Addition) to reduce out-of-band emissions, and we believe this technique will be used by manufacturers independent of the standards.

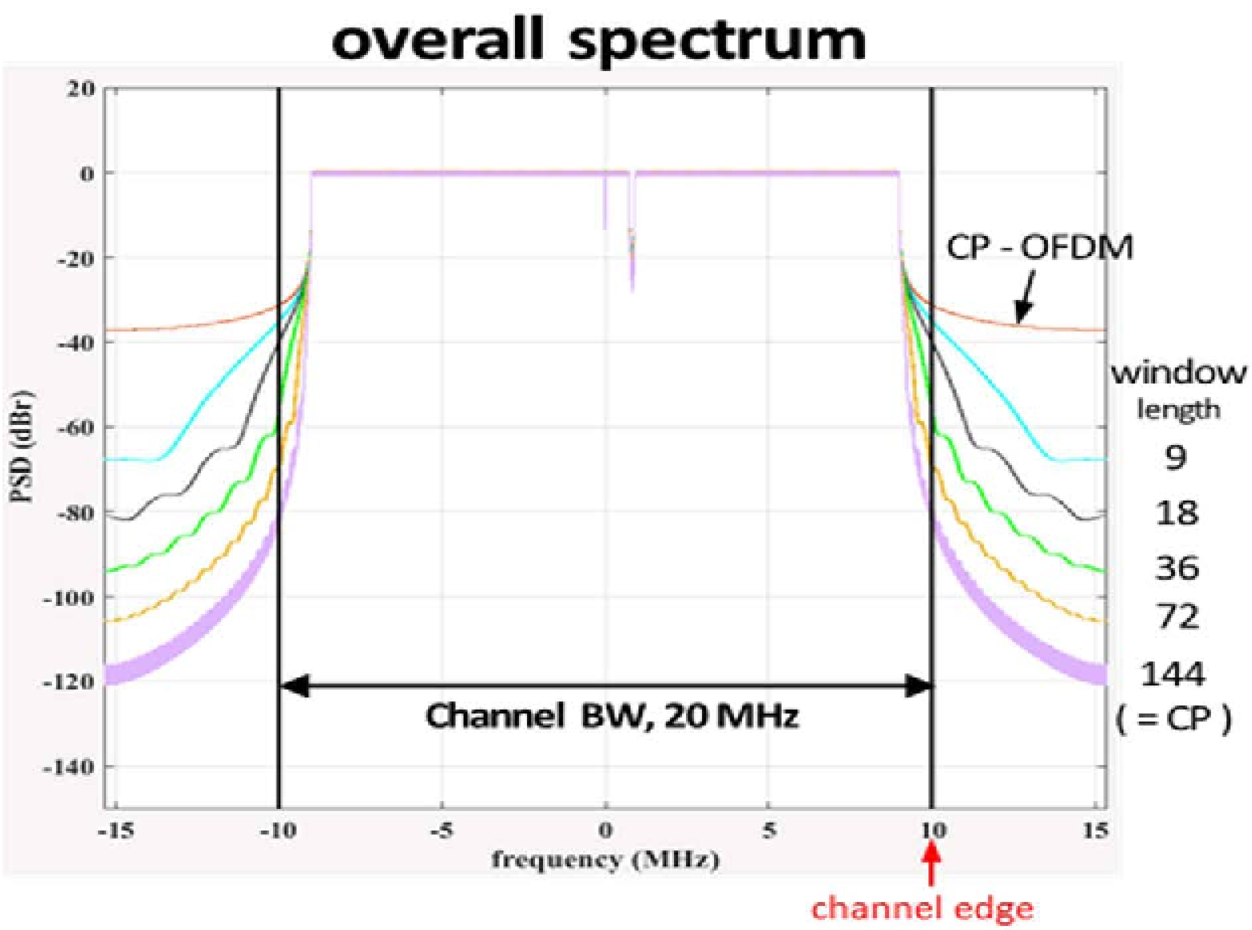

Figure 25. Out-of-band emissions for CP-OFDM with windowing

Source: Changyoung An et al, 2017 Ninth ICUFN

The ACLR specification for mm-wave systems has been set at 26- 28 dBc, substantially lower than the 45 dBc level required for LTE. The hard limit is still the same, at -13 dBm/MHz… however in the case of Massive MIMO systems we expect the relative specification (-28 dBc) to be the most relevant test. Note that -28 dBc applies to the 24-33 GHz band, while 37-53 GHz bands are relaxed to -26 dBc. This is fairly close to the prediction that we made two years ago, expecting the ACLR spec to be about -30 dBc. This decision was made between OEMs and operators as a way to ensure that silicon-based RF front ends would be possible…

Table 9.7.3.3-1: *BS type 2-O* ACLR limits

NR Channel bandwidth	BS adjacent channel centre frequency offset below the lower or above the upper Base Station RF bandwidth edge	Assumed adjacent channel carrier	Filter on the adjacent channel frequency and corresponding filter bandwidth	ACLR limit [dB]
[50, 100, 200, 400, …]	$BW_{Channel}$	NR of same BW	NR of same BW with SCS that provides largest transmission bandwidth configuration (BW_{Config})	28 (Note 1) 26 (Note 2)
NOTE 1: Applicable to bands defined within the frequency spectrum range of 24.24 – 33.4 GHz NOTE 2: Applicable to bands defined within the frequency spectrum range of 37 – 52.6 GHz				

Figure 26. ACLR specifications for 5G NR in mm-wave bands

Source: 3GPP

Based on these requirements, we do not see the vendors implementing DPD or Envelope Tracking in their mm-wave radios in the near term. Maybe in the long term these options will become a possibility, but for now the bandwidth makes these options impractical.

… Filters

5G system engineers are very reluctant to insert an RF filter into the RF front end, because filters in the 28 GHz band have roughly 1.5 dB of insertion loss that directly reduces the range of both uplink and downlink. The prevailing wisdom today is that "there's no interference in the mm-wave bands" so filters are typically used deeper in the block diagram, after the LNA/downconversion and before the upconverter/PA. In our view, this approach is temporary. In the United States, auctions are underway to license spectrum to the highest bidder, and as usual the auctions will place two competing operators in adjacent bands.

Will one operator's RU interfere with a second operator's RU? It's possible to manage the interference somewhat, through extremely careful RF planning, antenna placement, and T/R synchronization between competing operators. All three Korean operators have adjacent frequency blocks at 28 GHz, and they have already engaged in plans to set a fixed schedule for transmit and receive. However, three different RUs on a crowded street corner will have unpredictable multipath, especially with moving cars. Not everything can be modeled. In the end, we believe that interference will arise between competing carriers and between users, forcing 5G arrays to use filters.

Today, 5G mm-wave arrays don't use a specific component to filter the RF signal. All of the OEMs that we surveyed are introducing arrays with patch antennas that feed to a T/R switch with a via and a distributed three-dimensional metal trace. All together, these distributed elements provide some filtering to the RF signal. It's not the 40-50 dB rejection within a narrow bandwidth, but it can provide some 20 dB of protection from extraneous RF signals.

The ACLR specs have been set to be pretty light, so a filter is not necessary to control out-of-band emissions. Also, in the mm-wave bands, directional signals from radar, satellite, and other interfering sources will be unlikely to directly impact the receiver. So far, this plan has worked out okay.

Despite success in the field trials, we believe that the auctions and spectrum allocations in the USA and Korea will lead to a nonzero level of interference in these systems. Two users standing in a crowded subway station on competing mm-wave networks are likely to interfere with each other. When the interference reaches a point where about 5% of users experience reduced throughput, the operators will begin to ask for filters in the RF front end.

... Up/downconversion and IF

The most common RF architecture employed today involves the use of SOI-based T/R switches, LNAs, PAs, and up/downconversion to an IF frequency. All of these RF functions are integrated for multiple antenna elements on a single die, to make low-cost manufacturing possible.

The up- and down-converters translate the wide mm-wave signal down to a manageable IF frequency, using a simple RF downconversion like the good old superheterodyne transceivers of 2G days. The choice of IF frequency is different for each OEM, but ranges between about 4 GHz and 10 GHz.

Once the RF signal has been translated down to 10 GHz or below, the signal can be fed into a direct conversion receiver and digitized. Xilinx has a popular solution here, where multiple OEMs have chosen to use the Xilinx RFSoC with hardened logic for some standard processing, and programmable logic for beamforming and other functions that are likely to change over the next few years.

6 USER EQUIPMENT RADIO IMPLEMENTATION

Client devices for 5G will include handsets, tablets, PCs, mobile hotspots, fixed CPEs, and high-bandwidth IoT devices. The scope of this report focuses on broadband mm-wave client devices, so any low-bandwidth IoT applications are not covered here. The big challenges for these devices will be similar to previous generations of phones: driving to low cost, low power consumption, and small, simple radios.

Fixed Broadband: CPE Implementation

The first commercial 5G networks, already launched, offer fixed wireless access to residential users, at 24 GHz and higher. The development of CPEs has advanced over the past two years, to higher complexity because the RF link budget for this service is challenged. The first product launched by Netgear has horribly disappointing performance, with an EIRP of only +15 dBm…leaving the uplink very weak. We expect that products designed by mobile specialists will fare much better, where EIRP in the range of +40 dBm is typical.

Verizon and AT&T want to use CPE devices that are located indoors, near the user, with easy set-up to avoid an expensive truck roll. However, mm-wave signals do not penetrate buildings well, so at least 20 dB must be added to the link budget to account for NLOS reflections, attenuation through walls or windows, and other factors. Some of the additional gain has been provided through higher gain antenna arrays in the infrastructure. Samsung's approach so far has been to use 1024-element arrays to drive very high gain in the gNodeB antenna.

The major difference between a CPE and a smartphone implementation comes down to the number of antennas. Samsung's indoor CPE uses two 32-element arrays for a total +40 dBm EIRP. On the other hand, Netgear certified a "mobile hotspot" product with mm-wave sub-arrays taken from the handset ecosystem (estimated 8 or 16 antennas total), and achieves only +15 dBm EIRP. The level of performance will be absolutely obvious between these two products.

Based on the more advanced/higher gain CPEs, Verizon's trials have succeeded, with more than half of their CPEs located indoors, even with base stations located an average of 300 meters apart. We expect this large-array configuration to continue in both outdoor and indoor CPE products, limited only by the health+safety rules of indoor products.

Mobile Broadband: 5G Handset Implementation

More than 10 different handsets will be launched this year with mm-wave capability. Qualcomm's X50 and X55 chipsets take care of the extreme broadband baseband processing, and Qualcomm also supplies the RF transceiver to handle the direct-conversion RF processing for multiple antennas.

In the first introductory products, either three or four sub-arrays are used in the handset design, with antenna located on different sides of the handset. Antenna placement and the industrial design of the phone will be absolutely critical, as mm-wave signals are vulnerable to complete blockage by a hand covering an antenna. Foldable phone form factors and other innovations may ease this problem…essentially making the phone too large to completely cover with a human hand.

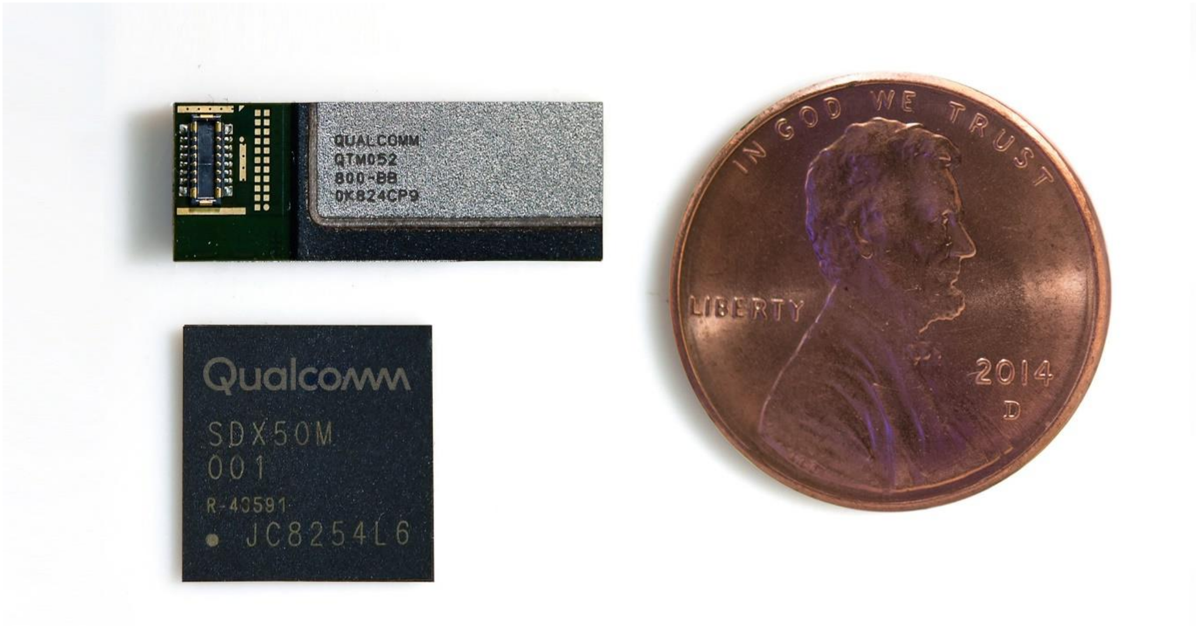

Figure 27. A commercially available mm-wave sub-array for UE implementation

Source: Qualcomm

The next big challenge will involve the synthesis of a steerable beam from a handset platform. Omnidirectional antennas—or nearly omnidirectional antennas—have been the norm in this market for thirty years, but in the mm-wave bands, antenna gain in the UE is critical to set up a useful uplink. This means that a mm-wave antenna array in the handset must include the ability to steer in three dimensions. We expect the steering and switching of multiple elements to become a basis for differentiation among handset vendors, with Qualcomm possibly offering a useful reference design. The beamforming challenge will not be easy, as three-dimensional steering of multiple antenna elements will require some processing power and each handset form factor will behave very differently. Any antenna element could be covered by the user's finger, so the algorithm will need to figure out how to optimize the antenna pattern with whichever antenna elements are available.

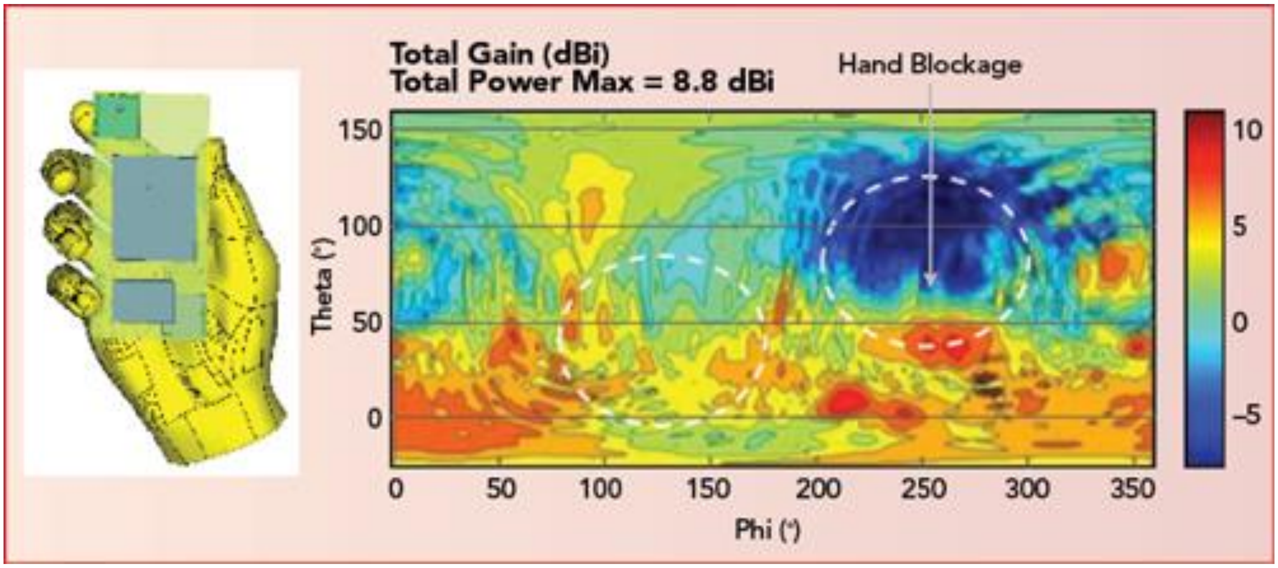

Figure 28. Simulated 3D mm-wave antenna gain with hand blockage

Source: Qualcomm

The sub-array in a handset is unlikely to achieve high gain due to cost and space constraints, but academic papers released so far indicate that 6-10dBi is a reasonable estimate for handset array gain. Even 6 dB could be the difference between a closed-loop TDD link and a complete loss of the 5G layer.

... Antenna sub-arrays

Each antenna sub-array is likely to consist of four antenna elements (dual polarized, this means 8 possible transmitter antennas and 8 possible receiver antennas). Each sub-array will also include the RF front end components (T/R switch, LNA, PA, and up/downconversion) so that multiple sub-arrays can be handled centrally by the direct-conversion transceiver. (Note that trying to route an RF signal at 28 GHz through the PCB of the phone would be ridiculously lossy, so up/downconversion is necessary to avoid having multiple transceiver chips in the phone). Three or four sub-arrays will be situated on multiple sides of the handset, in order to realize a three-dimensional steerable beam. This exercise is complicated by the presence of the user's hand. At 28 GHz the user's hand could reduce TRP and TIS by a devastating 30 dB.

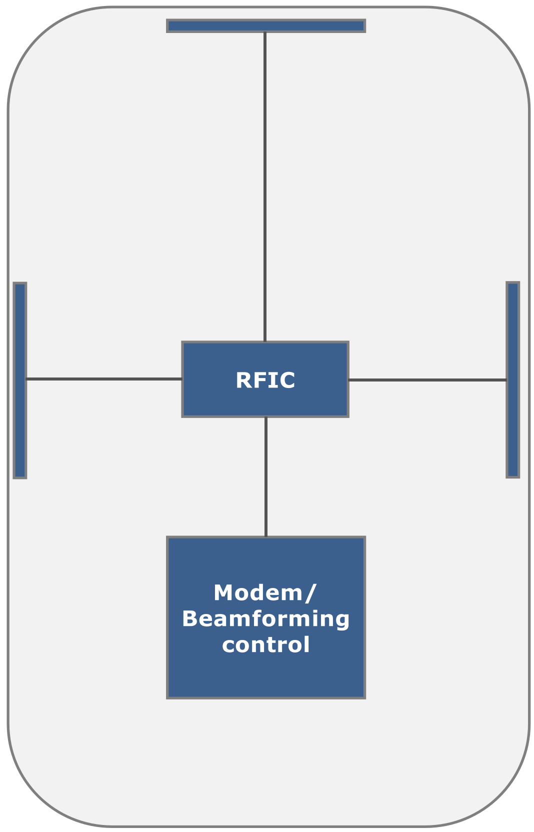

Figure 29. Layout of three mm-wave sub-arrays on a handset

Source: Mobile Experts

Qualcomm recommends the use of three sub-arrays per handset, laid out on the top and three sides of the handset. Based on this configuration, they expect to see +6 dBi gain or better, for 50% of the time. 90% of usage should experience at least +3 dBi of gain from the array. Note that simulations indicate that a fourth sub-array on the bottom of the phone would not be very useful in a typical upright position, but may be more useful in a "gaming" position or when the handset is used as a hotspot.

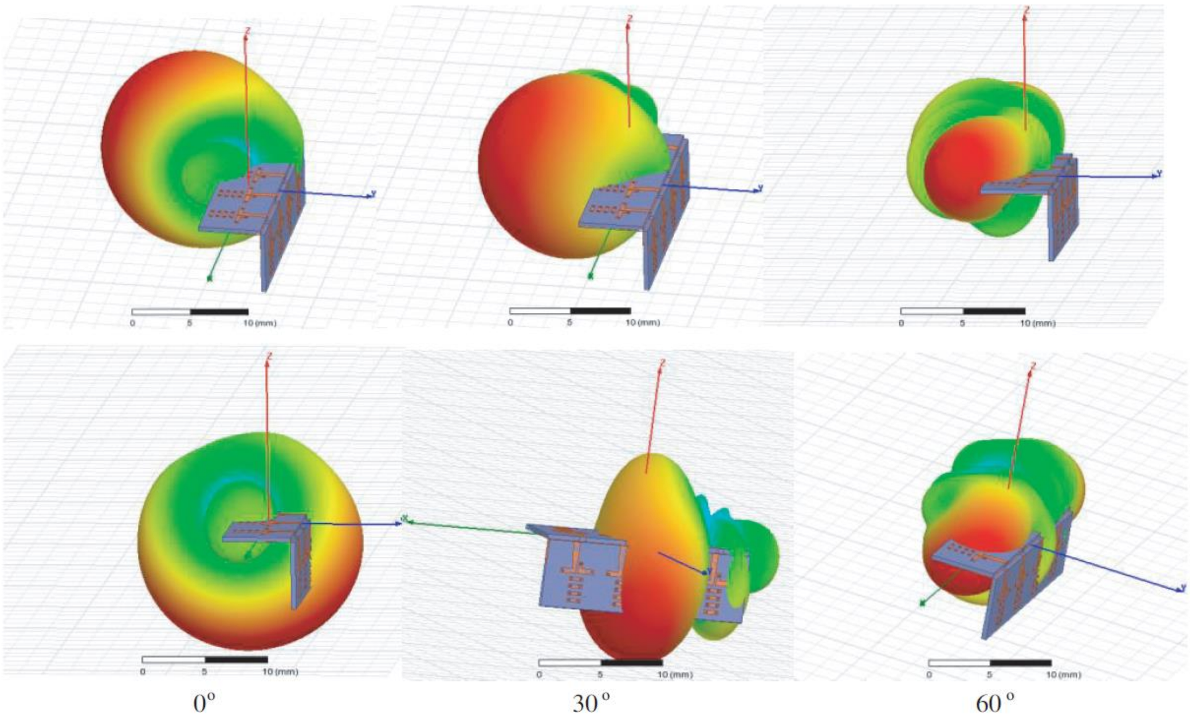

Figure 30. Various antenna patterns achieved with four 28 GHz antenna subarrays

Source: Shanghai University

To compensate for unpredictable hand placement by the user, the combination of antenna elements must be extremely flexible, allowing any combination of elements in the array to optimize the best possible beam pattern.

Figure 31. The Motorola 5G MOD product, 28 GHz

Source: Motorola

One concrete data point has been introduced already. The Motorola 5G MOD passed FCC certification at 28 GHz with EIRP up to 25 dBm (QPSK, at 100 MHz channel bandwidth). The EIRP was lower, at about +15 to +19 dBm, for 64-QAM at bandwidths up to 400 MHz.

... Semiconductor Considerations

Qualcomm's RF front end is the only option currently, so we don't have a strong basis for comparison between bulk CMOS, SiGe, SOI, GaN, and other potential options. Qualcomm uses an RF-SOI process to achieve high linearity and decent power output from each sub-array element: roughly +15 dBm linear power is our current estimate. Perfect use of four sub-arrays (16 total transmitting elements) could result in UE transmit power of +30 dBm EIRP or so. In real operation, we expect the EIRP to come out somewhere in the range of +20 to +25 dBm, as demonstrated by the Motorola 5G MOD product. This is similar to the EIRP of 1-2 GHz signals, but keep in mind that propagation is an issue at 20+ GHz.

Bulk CMOS and GaN are possibilities for the semiconductors in handsets, but we believe that for RF performance and cost reasons, the best choice will be RF-SOI. The amplifiers in the handset sub-arrays need to reach output power in the range of +5 to +10 dBm in linear operation, and bulk CMOS will not reach that level. GaN would easily quadruple the cost of the RF solution to $25 or higher per handset.

Overall, for cost reasons we expect that the 300 mm RF-SOI process will offer a balance of performance and cost. A high degree of integration between the RF front end and the up/downconverters will be critical to building a radio economically.

… Battery Life Impact of mm-wave 5G handsets

A millimeter-wave radio in the handset would consume higher power than a radio in the typical 1-2 GHz bands, due to poor propagation in higher frequencies, lower amplifier efficiency, and the processing needed for wideband, high-speed link. In this way, the viability of a mm-wave 5G handset will depend on the use case:

- Typical video download or streaming applications should be ok. In this case, the ratio of downlink to uplink can be at least 10:1. For this type of use case, the uplink would only transmit short bursts and the thermal and battery impact could be manageable. In downloading a video or another big file, the uplink requirement should be only for acknowledgement and operation less than 10% of the time.
- Two-way video applications such as "video chat" or VR gaming could be a problem. In a case where downlink-to-uplink ratio is 1:1, we can expect the mm-wave transmitter to operate in a continuous duty cycle. Notably, we don't currently have any applications which would drive a need for 100 Mbps or more in continuous symmetrical operation. Assume that the continuous stream would average about 20 Mbps (compared with HD video at less than 10 Mbps). In a practical sense, the 5G radio would operate at 200 Mbps, about 10% of the time to provide the user with a perceived 20 Mbps experience.

In TD-LTE networks today, the power from the uplink transmitter is already an issue, and we expect that the link balance will not improve as we move to higher frequencies.

This means that the Class 2 power levels of TD-LTE (HPUE) are a minimum level that will be necessary from the handset, at least in terms of equivalent EIRP. At 2.5 GHz, TD-LTE is moving toward high power operation in an attempt to balance the link budget, boosting the handset transmitter by about 3 dB to about +23 dBm. Given the efficiency of GaAs amplifiers at 2.5 GHz, at about 45%, this approach dumps about 1.5W of heat into the handset.

	RF Power level	DC Power Dissipation
Modem	--	---baseline case--
Transceiver	Low	--baseline case--
Power Amplifier	+27 dBm at output	1.1 Watts
Filters/Switches	+23 dBm to antenna	--
	TOTAL	1.53 Watts in operation
	50% duty cycle	0.76 Watts average

Figure 32. Estimated DC power consumption for TD-LTE PA at 2.5 GHz—video chat case

Source: Mobile Experts

For now, we assume that at 28 GHz at least two transmitters will be active at the same time, to achieve some rudimentary steering.   Power amplifier efficiency will be lower at 28 GHz due to the higher frequency, but the lighter ACLR requirement means that efficiency may not be as bad as previously anticipated.   We're estimating 35% efficiency for the 28 GHz PA.

	RF Power level	DC Power Dissipation
Modem	--	400 mW (extra for wider bandwidth for 5G NR)
Transceiver	Low	30 mW
Power Amplifier (x2)	+27 dBm at output	1.43 Watts (x2)
Filters/Switches	+23 dBm to antenna	--
	TOTAL	3.29 Watts in operation
	10% duty cycle	0.33 Watts average

Figure 33.   Estimated DC power consumption for 5G NR PA at 28 GHz—video chat case

Source: Mobile Experts

These tables lead us to an interesting conclusion: 5G will actually save power in the battery, because for today's applications, 5G speeds are not necessary and the radio can turn off for 90% of the time. Any future problems will arise if new applications (VR gaming??) drive the uplink to a 50% duty cycle, where 1.6W of extra heat will be hard to manage inside a smartphone.

Mobile Broadband: 5G Hotspot Implementation

Because the performance of 5G mm-wave handsets will be challenging, we're starting to explore the idea that mobile operators will push end users toward the use of hotspots.   AT&T has indicated that the "puck" will be an important part of their plans. Verizon has started with fixed CPEs.   We believe that this concept is more sensible than the use of mm-wave in handsets, for multiple reasons:

- Mobile hotspots don't have the user's hand blocking the antennas during operation.
- Mobile hotspots can have bigger batteries than handsets.
- Mobile hotspots can include larger numbers of antennas, with more flexibility on antenna placement.

Figure 34. A 5G mm-wave mobile hotspot

Source: Netgear

Overall, while the Netgear product was a complete failure to meet the need, we expect mobile hotspots to arise with performance similar to the fixed CPE market, enabling users to continue working with Wi-Fi on their smartphone. In this way, the operator achieves the cost savings of the low-cost mm-wave network, and the end user gets higher speed and larger data bundles.

Mobile Broadband: PC and Tablet Implementation

The inherently low cost per GB on a 5G mm-wave network raises an important question: Will it be cheap enough to replace Wi-Fi as the primary connectivity for laptops and tablets? A combination of LTE and 5G would certainly be easier for the end user to manage than Wi-Fi, so companies like Dell and HP are now offering "always connected" PCs that simply rely on unlimited LTE plans today.

The implementation of mm-wave solutions in a PC or tablet will be similar to the smartphone market, in the use of multiple sub-arrays spread widely on different parts of the platform. In this case, however, the power budget will be higher so the number of antenna elements could be higher, resulting in superior uplink power.

7 COST ESTIMATES

Network cost is the primary reason that mobile operators are investing in mm-wave. A network includes a lot of fixed costs, such as tower rental, fiber costs, and core network costs. Spreading the fixed costs over a larger number of GB has a simple result: Lower cost per GB.

The other major cost factor relates to the cost of mm-wave implementation in the user equipment. Handset or CPE costs must be reasonable, including the cost of the components inside as well as the practical costs related to supporting the client devices.

Infrastructure—Cost per GB delivered

The total cost of ownership for 5G mm-wave infrastructure will come down to the cost of the RAN equipment itself, as well as the range achieved by each radio. 5G mm-wave radios will be more complex and more expensive than any previous generation of RAN equipment, but the sheer weight of data carried will be an order of magnitude higher. As long as operators can achieve a decent range from the radio unit, the cost per GB can be reduced.

Mobile Experts looks at multiple cost factors to estimate Total Cost of Ownership:

- Site acquisition;
- Radio equipment;
- Backhaul/fronthaul equipment or leasing;
- Core network equipment;
- Deployment and testing costs; and
- Operations and maintenance costs over an eight-year period.

The impact of adding 5G capacity can be dramatic. The operator can reduce the cost per GB of data from $1 per GB to less than $0.10 per GB.

It's important to note that the dramatic cost savings shown below can only be available in locations where the capacity will be *utilized*. In other words, mm-wave networks are a great idea, but only in places with huge demand for mobile traffic.

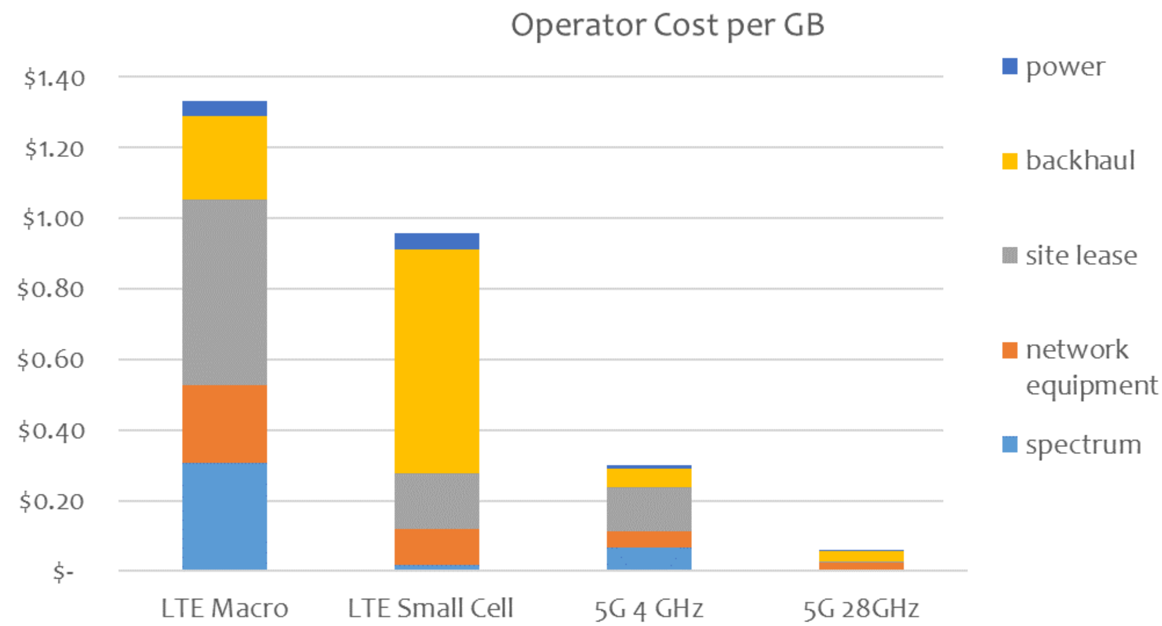

Chart 2: Cost per GB: Comparison of LTE and 5G networks, at 4 GHz and 28 GHz

Source: Mobile Experts

Infrastructure—Cost per square kilometer of coverage

Looking at cost for capacity is the primary metric for operators, but they must balance the cost estimates per GB with cost per square kilometer. Additional capacity is extremely cheap at 28 GHz, but the cost to adequately cover a large area is prohibitively expensive.

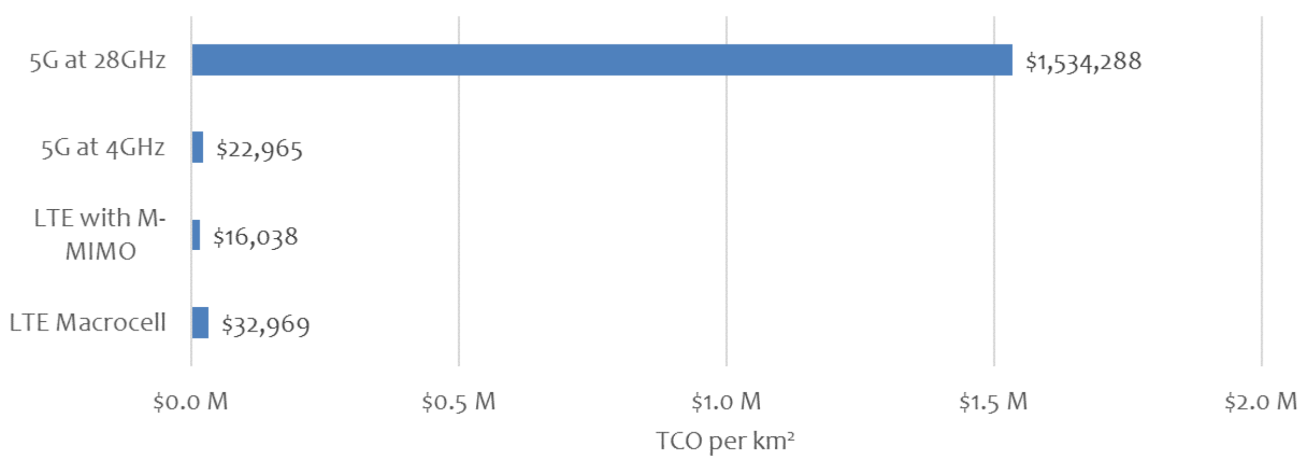

Chart 3: Cost per km²: Comparison of LTE and 5G networks, at 4 GHz and 28 GHz

Source: Mobile Experts. Assuming 64T64R for both 5G networks. Assuming +60 dBm EIRP at 28 GHz

Taking these two cost factors together, the deployment plans for the operators become more clear. We find that the choices for 5G infrastructure present some great opportunities for cost reduction, but have limited applicability. In the chart below, the 28 GHz systems shown so far at +60 dBm have great potential as a high-capacity layer in the mobile network because the cost per Gbps of capacity is quite low.

Of course, the long term goal is to achieve both low cost/km2 and low cost/Gbps. We expect ongoing development of 5G mm-wave solutions for longer range applications, in an attempt to reduce mm-wave cost per km2. GaN-based amplifiers may be one tool here, to increase downlink EIRP to the range of +70 dBm, for suburban use where additional downlink capacity is needed. The uplink could remain a problem, but CPEs and hotspots with high-gain antennas may come into play over time.

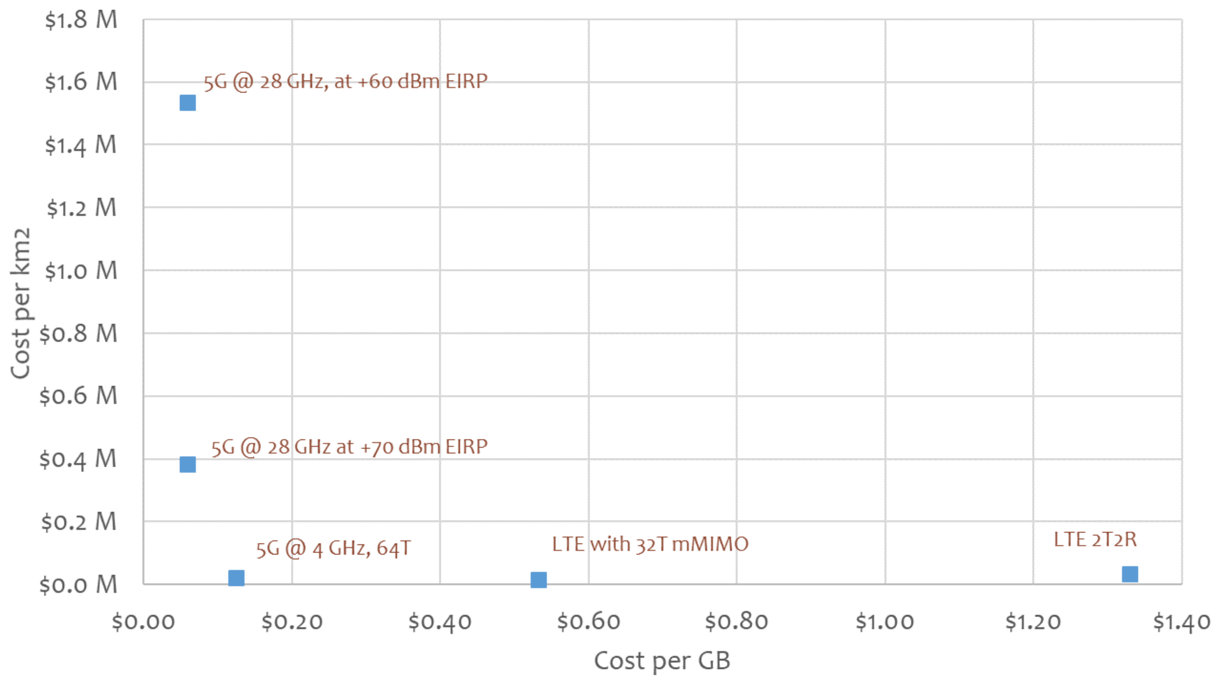

Chart 4: Cost of Coverage vs. Cost of Capacity for 5G

Source: Mobile Experts.

Fixed-Wireless CPE Cost

Development of CPEs for mm-wave systems have advanced dramatically, and attention to this opportunity by Qualcomm, Intel, and other semiconductor players has brought down the cost significantly. Key factors in the cost equation include:

- **Massive MIMO sub-arrays.** At 28 GHz, vendors are using up to 32 antenna elements in order to get very high antenna gain from the CPE. This means more complex radios and beamforming algorithms. The CPE will require a basic size to support the antennas, beamforming and baseband processing, and the power supply.
- **Semiconductor integration**. Compared with low-volume LMDS equipment from the 1990s, the BOM for these components will be quite inexpensive. We anticipate tight integration of the RF solution with the antenna elements and the up/downconverter to create an RF solution in the range of $30 or so. Possibly significantly less, depending on volume.
- **Indoor vs. Outdoor.** With high-gain antennas on the AP and the CPE, more than half of Verizon's field trial units can use an indoor CPE. This means that the unit doesn't need to be weatherproof.
- **Truck rolls.** Indoor CPEs with zero-touch configuration can avoid the expense of a visit by a technician. Rural fixed-wireless operators report an average cost of $200 per truck roll. This sounds low, but we've used this figure in our estimates.

Overall, we estimate the cost of an indoor CPE to be about $250, based on a semiconductor BOM of about $100. An outdoor unit should cost about twice as much, or about $500. The operator will need to carry the $200+ cost of a truck roll for outdoor units, and we expect some customer service cost associated with all CPEs, despite the intention to offer a zero-touch solution. These connections will be tricky, and consumers will not place the CPE near a window as instructed.

Handsets and Tablets

Handsets will be a difficult challenge for 5G above 6 GHz, so one big open question remains unanswered: Will handsets use mm-wave directly, or will consumers move to tablets, foldable devices, or hotspots in order to avoid the technical problems with antenna blocking?

One major issue is the cost of the additional radio components. A handset or tablet with 5G at 20-40 GHz will include fairly significant costs….enough that a global SKU is unlikely to include mm-wave simply to have the "latest bands" in the phone. In this case, we're dealing with multiple sub-arrays, so the implementation of mm-wave involves at least 4 or 5 new components on the handset.

In fact, the financial cost may be less important than the space taken by the mm-wave sub-arrays and the RF transceiver/modem. The additional components will require several square millimeters of PCB space, which is a precious commodity in the smartphone. The practical impact of using additional board space will be the shrinkage of the battery, so component size directly impacts something that consumers care about.

Here's a rough breakdown of the likely BOM costs for a mobile 5G implementation at 28 GHz:

Component	**Number per phone**	**Cost per component**
Antenna/PA/LNA/Switch/Downconverter module, 3 RF sub-arrays per module	3	$1.00 per module
Transceivers	1	$0.60
Modem	1	$3.00 (additional cost for bandwidth and beamforming)
		$6.60 total

Figure 35. Additional BOM cost for 5G in mobile devices, 28 GHz

Source: Mobile Experts

8 MILLIMETER WAVE NETWORK OUTLOOK

The fundamental outlook for mm-wave network deployment has increased over the past three years, mainly because American mobile operators need additional capacity and C-band spectrum is still unavailable.

As illustrated in the Mobile Experts 5G Broadband Business Case, Verizon and AT&T are likely to run out of capacity in the bands below 6 GHz within the next four years. Even with the use of LAA, CBRS, and new C-Band spectrum, these companies don't have enough spectrum to keep up with the consumer trend.

As a result, we predict that the existing LTE small cell sites in the USA will start to be outfitted with 5G mm-wave gNodeB radios.   Operators have been preparing for this by using fiber to almost all small cell sites, and leaving some flexibility in their legal arrangements to allow for upgrades on streetlights and other low-height locations.

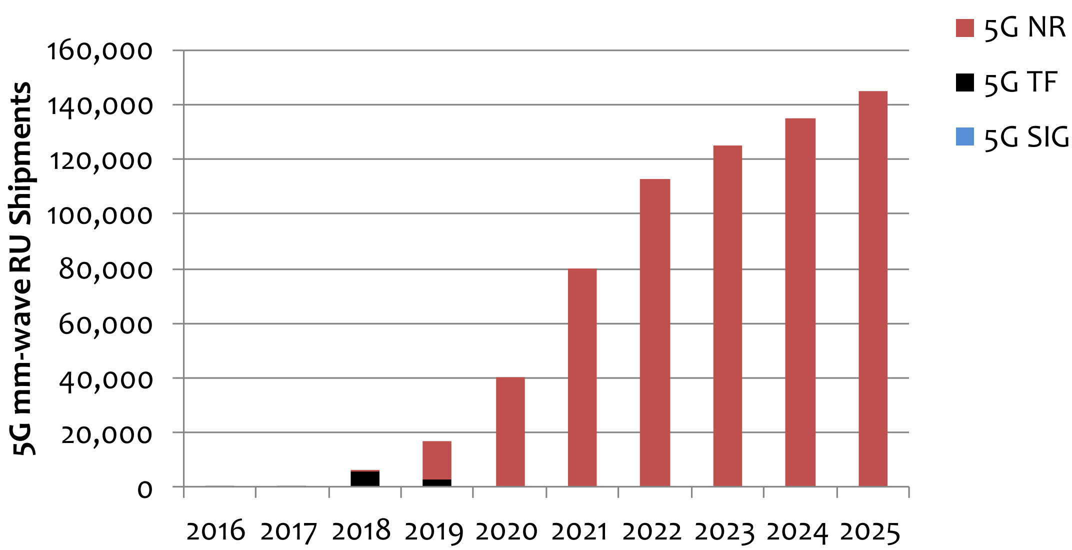

Chart 5:   5G mm-wave RU Shipments, by standard, 2017-2025

Source: Mobile Experts

In particular, the 5G NR standard will take over from the pre-5G configurations used in Korea and the USA.   By mid-2020, we expect all deployments in the 24-39 GHz bands to be compliant with 5G NR, whether used for fixed or mobile access.

5G mm-wave Infrastructure

Verizon's early 'land grab' of the 28 GHz band will work out to be a big advantage for them, as Verizon will be able to deploy a fairly consistent solution across dozens of US cities. AT&T is behind, with reasonable geographic coverage but more focus on the 24 GHz band. The 39 GHz band will also have its place, as each operator will use this band where a lower band is not available in a key city. Note that Korean operators will also contribute to the strongest element here with base station deployment at 28 GHz.

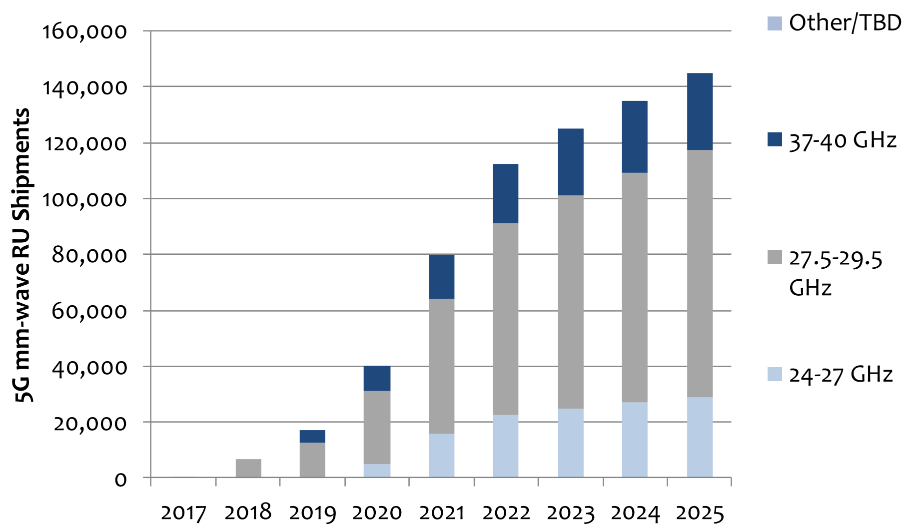

Chart 6: 5G mm-wave RU units shipped, by frequency range, 2017-2025

Source: Mobile Experts

Clearly the US market will dominate this segment for several years. It's not that the US market is so advanced compared with Japan, China, or Korea. This simply comes down to the lack of near-term availability of spectrum in the 3-5 GHz range, so the US operators are forced to move higher in frequency to get some bandwidth.

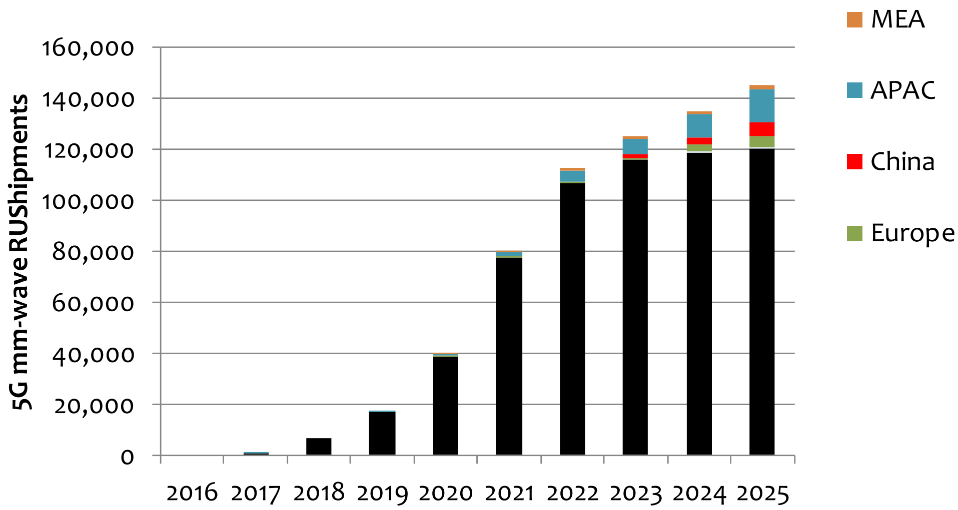

Chart 7: 5G mm-wave RU shipments, by world region, 2017-2025

Source: Mobile Experts

The markets in Korea and Japan are relatively small, but will represent 5-9% of the mm-wave RAN forecast because of the large areas of Tokyo and Seoul with high density. China will eventually come along, but we expect Chinese operators to focus their money on the 2.6 to 4.9 GHz bands for the next six years, starting serious investment in mm-wave after 2025. The density of traffic in Europe is not as high as Asia or the USA, so we expect Europe to focus on sub-6 GHz 5G for the next 7 years.

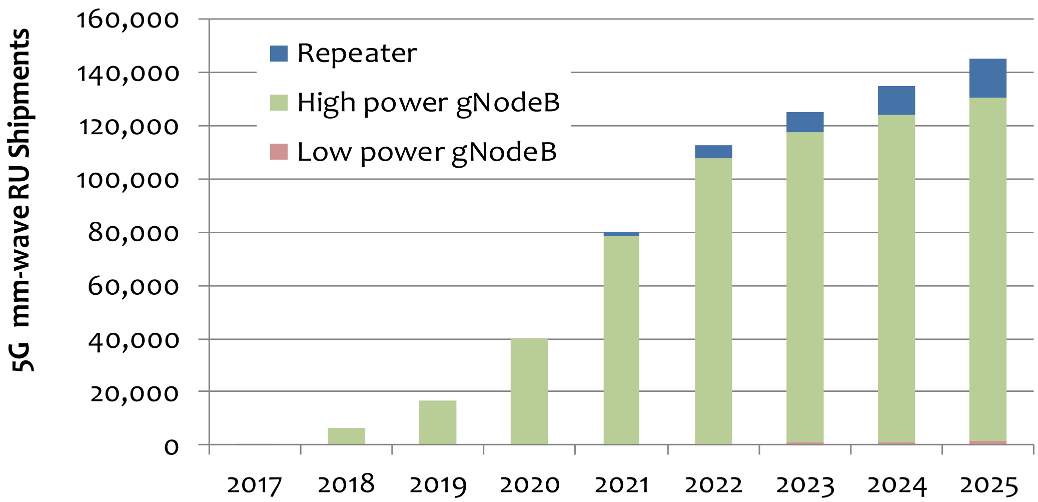

Chart 8: 5G mm-wave RU shipments, by indoor vs outdoor, 2017-2025

Source: Mobile Experts

Almost all of the mm-wave deployment that we foresee in the first five years will be outdoors. There are some interesting applications in stadiums and other high-density venues, but we expect the number of units shipped into that specific application to be measured in the hundreds for a few years. Repeaters, on the other hand, hold some promise in challenging urban locations with buildings or other obstacles. Repeaters have not been a mainstream product for operators in the 1-2 GHz bands, primarily because of concerns about pilot pollution (interference) reducing system capacity. In this case, however, the mm-wave spectrum may have capacity to spare, and coverage is a bigger issue. For those reasons, we believe that repeaters have a chance in this round.

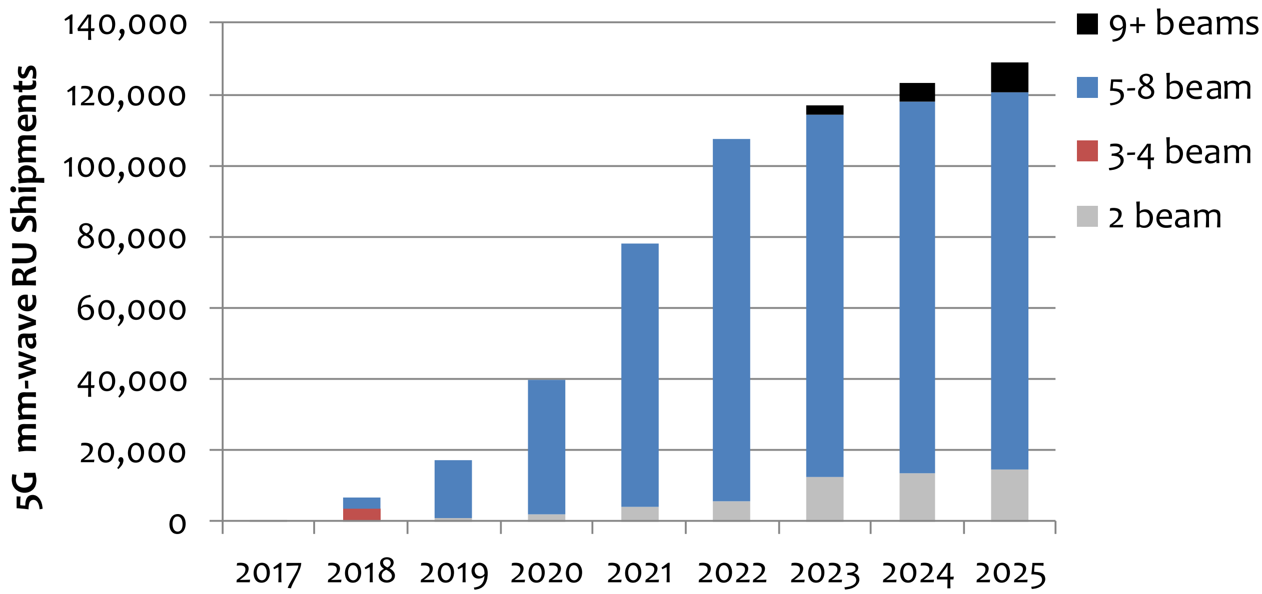

Chart 9: 5G mm-wave RU shipments, by number of beams, 2017-2025

Source: Mobile Experts

The first 5G mm-wave base stations only supported a single 64T panel, and in most tests a single beam was used. However, the huge capacity of MU-MIMO cannot be overlooked, so today most OEMs are moving toward software to support 4-8 beams per sector. This feature is reconfigurable, so the same product can be optimized for fewer beams and longer range, or higher capacity and shorter range. (Of course, building in extra radios and capacity for the extreme cases would be expensive, so in the end, hardware will be optimized for key cases). Four panels with 64T64R per panel (total 256T256R) allows for four independent beams at high EIRP, and much higher capacity. The market requirement calls for high enough capacity to justify this kind of additional complexity.

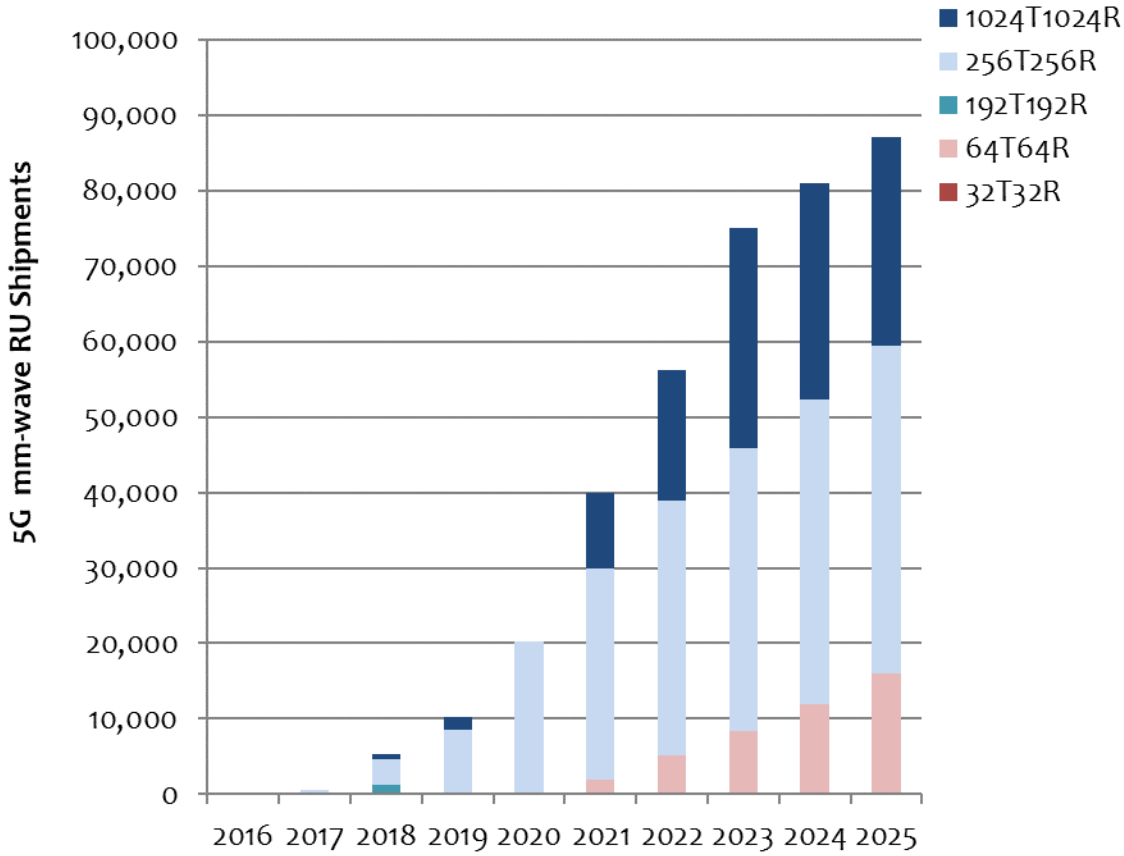

Chart 10: 5G mm-wave RU shipments, by transceiver configuration, 2017-2025

Source: Mobile Experts

Today's early products include three or four panels with 64 elements per panel. We expect the number of antenna elements and the EIRP to increase together over the next few years, with 1024 elements per sector becoming a common configuration. In the longer term, there's also a possibility of 32T or other lower-complexity radios using fanout structures with high EIRP, to cover suburban markets.

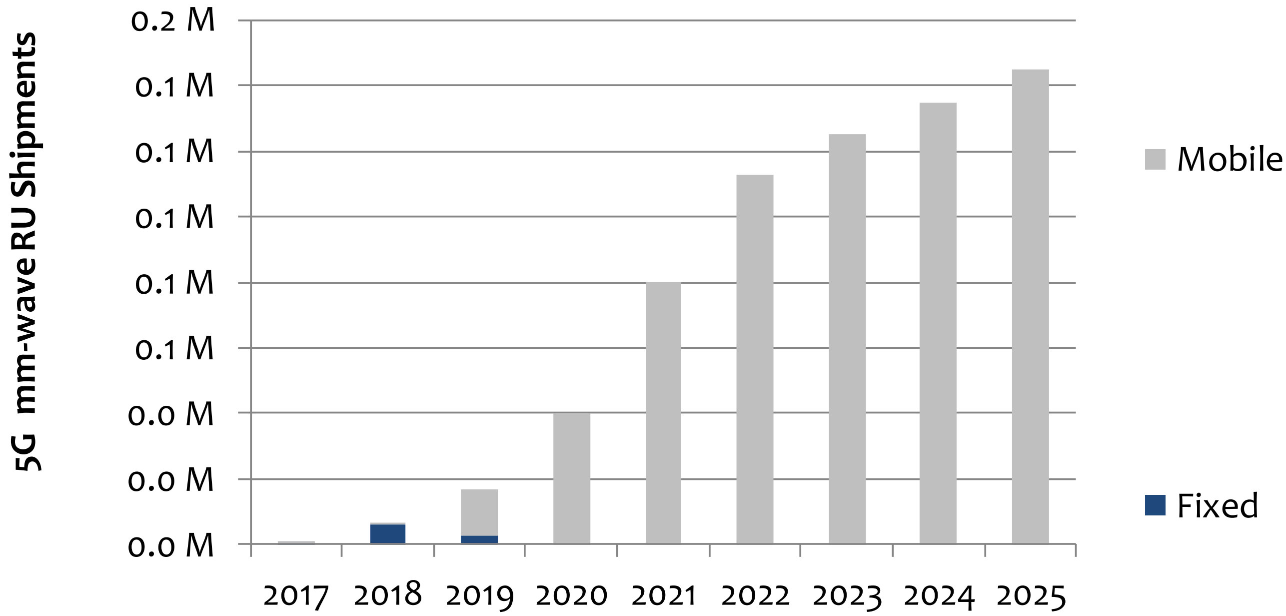

Chart 11: 5G mm-wave RU shipments, fixed vs mobile, 2017-2025

Source: Mobile Experts

We don't like to talk about "fixed" and "mobile" in the context of wireless broadband, because we believe that these terms will be obsolete in a few years. The fact is that most "mobile" broadband involves a person that is sitting in one position, streaming video. The operators will migrate their traffic so that all of the traffic runs over the mobile standard, whether it's used for nomadic users, fixed users, or true mobile users.

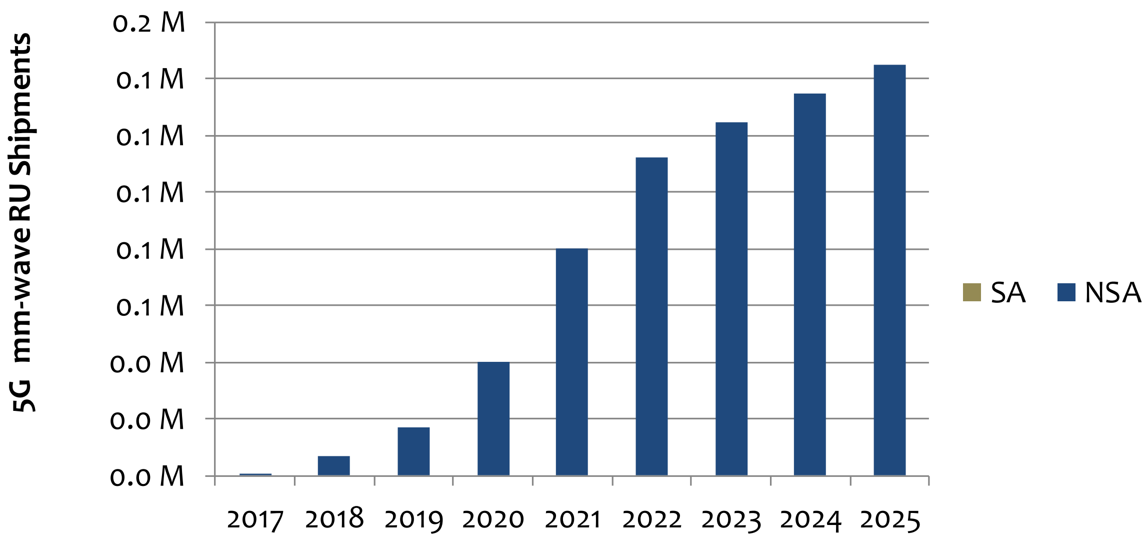

Chart 12: 5G mm-wave RU shipments, NSA vs SA, 2017-2025

Source: Mobile Experts

The eventual goal for the operators involves the use of Stand-Alone networks (where the 5G core network takes the lead and no LTE control channels are required). In the case of 5G mm-wave, this dream is pretty distant. We don't see the mm-wave link having the reliability to stand alone for several years, if ever. So, even when the core network is ready, we do not anticipate mm-wave operators migrating to SA.

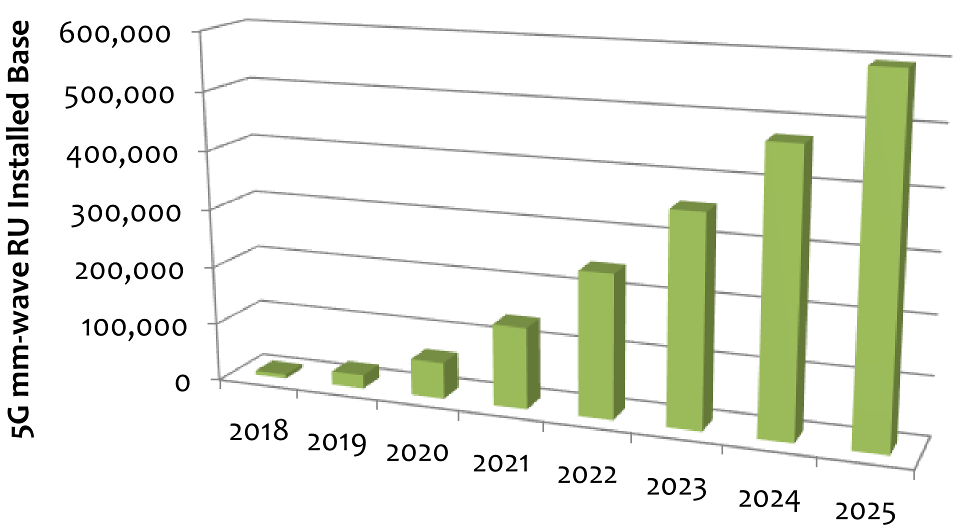

Chart 13: 5G mm-wave RU installed base, 2018-2025

Source: Mobile Experts

9 MILLIMETER WAVE CLIENT DEVICE OUTLOOK

5G mm-wave Fixed CPE units

The early deployment will be based on fixed deployment of Customer Premises Equipment, serving the Verizon FWA network. We expect some quick growth as the trial network at Verizon is upgraded to 5G NR. After mid-2020, we expect Verizon to open up this network to a larger group of people in multiple cities, with widespread marketing and a few million customers signing up per year.

Over the longer term, the "fixed" market may not grow because it will be replaced by the "mobile" hotspot market. So, the CPE shipment chart has stunted growth.

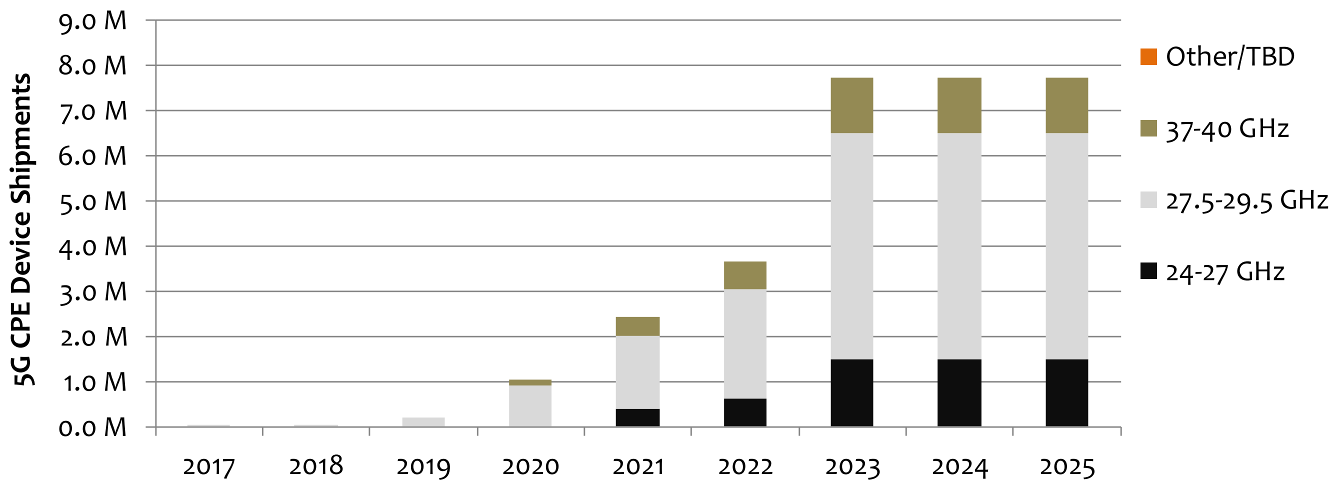

Chart 14: 5G mm-wave Fixed CPE Shipments, by frequency band, 2017-2025

Source: Mobile Experts

5G Handsets, Tablets, and Hotspot devices

Devices are coming to market very quickly for 5G mm-wave. Netgear has already introduced a mobile hotspot at 39 GHz for the AT&T network, and we expect at least 10 smartphones to be launched in late 2019. Qualcomm has been sampling chipsets for several months already, so there is a definite market "push" to be first with 5G devices.

Despite the big push, we are skeptical about 5G mm-wave in smartphones. The introduction of sub-arrays from Qualcomm is impressive, as the slim form factor, efficient performance, and high performance look pretty good so far. But we expect the hand-blocking issue to be difficult to surmount in the real world, as users will simply cover the antennas with their hands and ideal performance will be elusive. The simulations in Figure 28 are not promising so far, with only 5 dB antenna gain typical from a handset.

Foldable or expandable smartphone form factors may change the equation… providing more room for the antennas to spread out and avoid hand coverage. But we believe that hotspots will be preferred to smartphones.

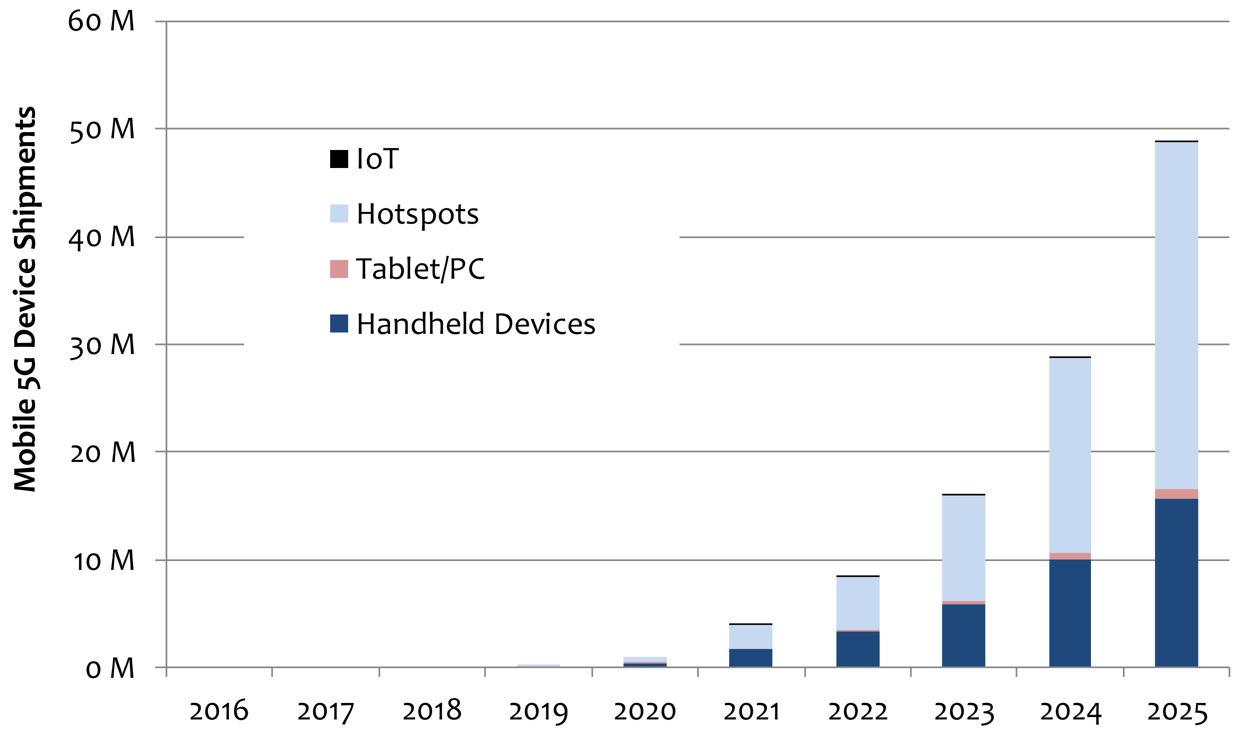

Chart 15: 5G Mobile User Device Shipments, handset vs hotspot vs IoT, 2017-2025

Source: Mobile Experts

A few signs point clearly toward hotspots as a better alternative than mm-wave smartphones:

- The heaviest usage of 'mobile' data takes place at home.
- End users get little benefit from the speed of 5G, so operators will be forced to incentivize the user to adopt a 5G mm-wave device.
- Users have strong preferences related to battery life, size, cost, and other features of the smartphone, so operator incentives in the phone market will get expensive.
- Operators can give away free hotspots that cost $200 or less, thereby offloading the key residential traffic easily.
- Plug-in hotspots that are transportable but not necessarily battery-powered can use higher-power amplifiers and can achieve a superior link budget for 5G operation.

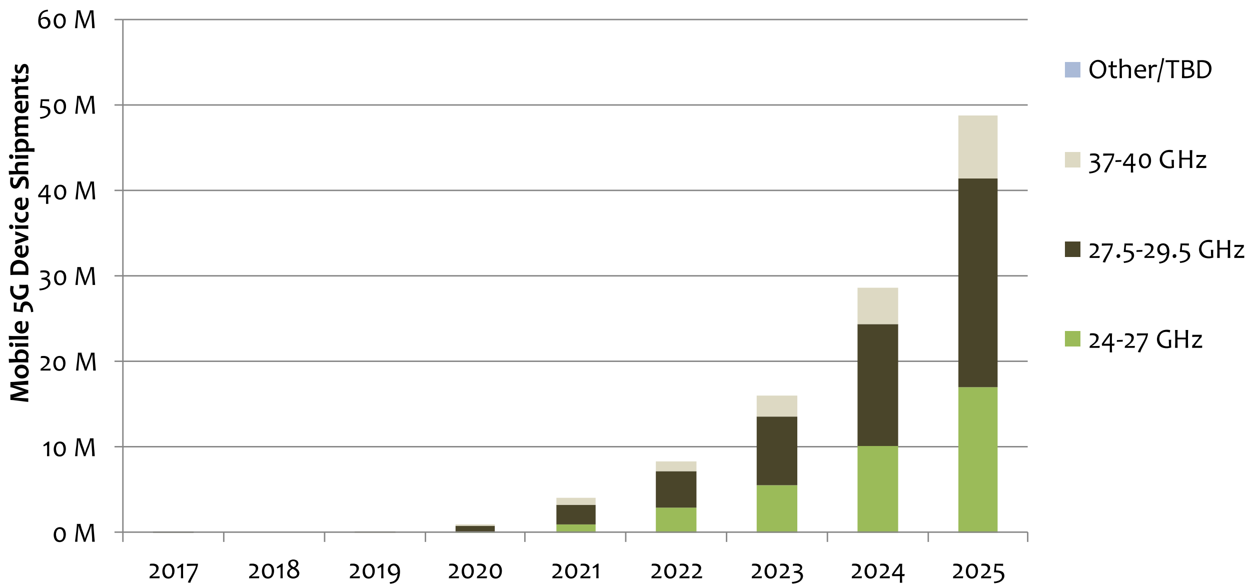

Chart 16: 5G Mobile User Device Shipments, by frequency band used, 2017-2025

Source: Mobile Experts

The frequency bands used in mobile devices will be concentrated in the same way that the networks will be focused at 28 GHz, 24 GHz, and 39 GHz. In fact, the radios available for handsets today are wide enough to cover all three bands, so we're showing the primary use of the device. We expect many of these devices to be capable of multiple mm-wave bands.

Broadband IoT devices such as drones, security cameras, and autonomous vehicles will constitute a relatively small fraction of total 5G client devices. Note that we have excluded IoT devices that simply use the low latency or high reliability of the 5G network….in the scope of this study we are primarily concerned with broadband applications of 5G networks.

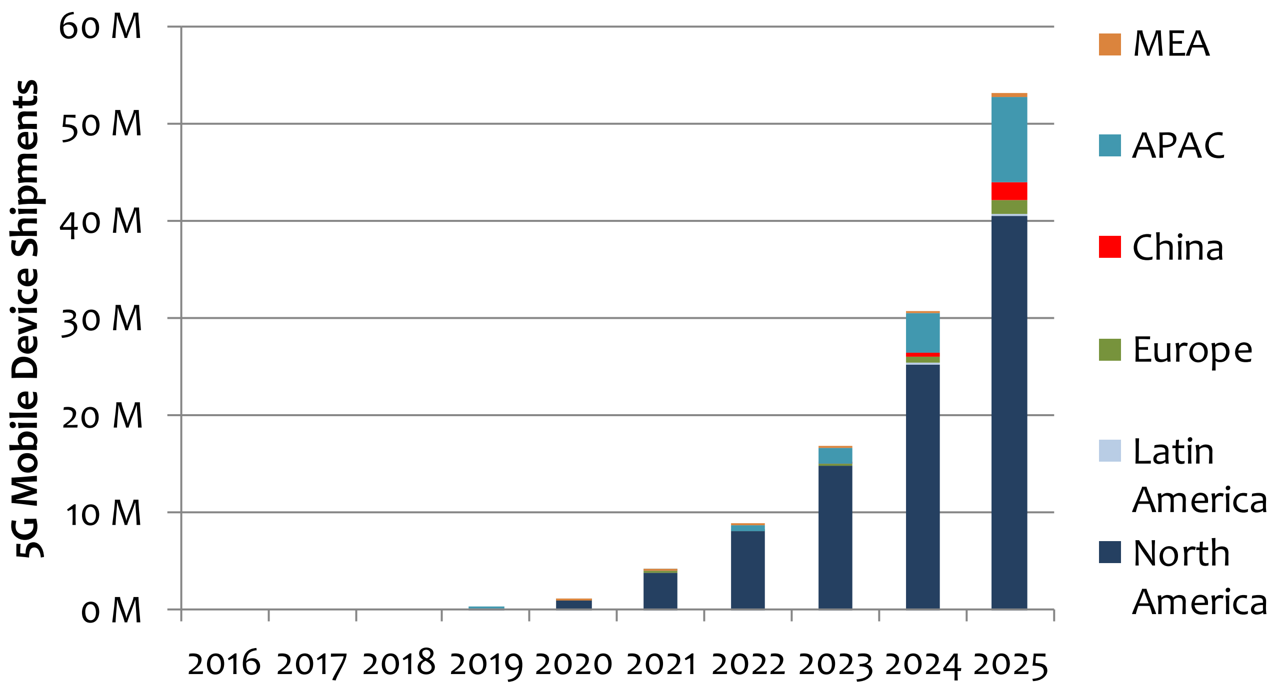

Chart 17: 5G Mobile User Device Shipments, by frequency band, 2017-2025

Source: Mobile Experts

Another important aspect to consider: The United States and Korea will be the only countries with significant 5G mm-wave networks for a few years. That means that global SKU products are unlikely to include 5G mm-wave, and we can expect the bulk of the market to consist of more localized products that are tailored for the US market.

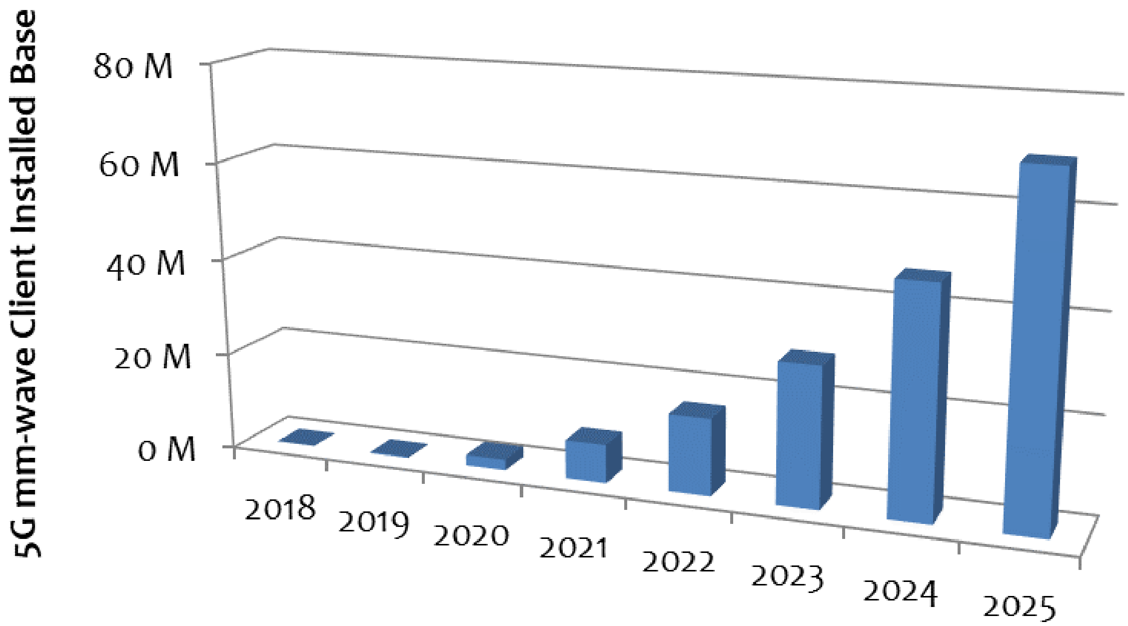

Chart 18: 5G Mobile User Device Installed Base, 2018-2025

Source: Mobile Experts

10 COMPANY PROFILES

3D Glass Solutions

3D Glass is a small company that provides RF glass packaging solutions for high-density manufacturing. The company can embed multiple die in a multi-layered glass structure that can be configured with metal traces and vias for distributed matching elements and filtering.

Analog Devices

ADI is a strong supplier for ADCs and DACs in mobile communications, and with their acquisition of Hittite Microwave they have the ability to put together the RF CMOS transceivers and compound semiconductor front end components in heterogeneous assemblies.

Anokiwave

Anokiwave has surged into a very strong position in the market for mm-wave beamforming arrays, with multiple major design wins. The company has settled on a 300 mm RF-SOI process for high volume production and low-cost integration.

Broadcom

Broadcom/Avago has supported millimeter-wave markets for over thirty years, with a strong amplifier capability. The company also has strong filter capability which might apply at 3.5-6 GHz but probably not at mm-wave frequencies.

Ericsson

At Ericsson, radio technology has always been a strength, and the company comes into the 5G market with deep capability in the integration of the radio, antenna, and baseband processing. Ericsson also recently agreed to acquire Kathrein-Werke, which adds significant antenna depth to the team. Ericsson has also invested heavily in virtualized core networks and Cloud infrastructure to support mobile applications. Ericsson has emerged as one of two suppliers supporting production deployment at 28 GHz for Verizon and AT&T, with multiple mm-wave products available now.

Gapwaves

Based in Sweden, Gapwaves develops antenna arrays based on GaN and "Artificial Magnetic Conductor" structures which dramatically reduce feed losses in mm-wave antenna arrays. The open waveguide approach holds potential for integration of filters, active components, and steerable antenna arrays.

GlobalFoundries

GlobalFoundries has strong mm-wave capability as a foundry and semiconductor fab using RF-SOI and SiGe technologies. GlobalFoundries has taken the primary production position in fabricating high-volume devices for Anokiwave and other key semiconductor suppliers.

Huawei

Huawei is the world's leading RAN vendor, with 40%+ market share in radio shipments for 2G through 4G. Huawei has shown mm-wave demonstrations at trade shows, but has very little meat on the bones. Because Huawei is excluded from the US market, their available opportunity in mm-wave is very small for the next few years.

Infineon

Infineon has strong SiGe capability, and produces automotive radars in huge volume at 24 GHz and 77 GHz. Infineon combines capability for SiGe, BiCMOS, GaN, and RF CMOS, so they have the ability to put together a multi-chip module with complete radio functionality. They have achieved at least one major design win for 5G mm-wave so far, as the major OEMs are hedging their bets between SiGe and RF-SOI.

Intel

Intel offers a modem with mm-wave capability NR handsets. Introduced in January 2017, the Intel modem is a first step and so far we have not seen the logical second step: a multi-mode modem with the necessary RFIC/beamforming/sub-arrays for volume production.

Of course, Intel is also very much involved in the infrastructure market, with baseband processing and the implementation of Virtualized RAN systems using the X86 architecture. The two business areas are separate but Intel's strong presence in the Cloud RAN area gives them a window into upcoming 5G deployments.

Finally, Intel demonstrated a 5G repeater recently, to illustrate a battery-based repeater concept. Intended for busy-hour use or possibly in venues that have a short surge of traffic, the mm-wave repeater could extend the range of 5G RAN infrastructure with in-band backhaul.

Motorola

Motorola's innovative "mod" product line provided them with a quick opportunity to introduce the first handset for Verizon's 5G NR network. The "5G MOD" uses four sub-arrays, The modularity of this product line allows for the handset user to switch modules for different bands, or for future upgrades.

Movandi

Movandi is a stealthy start-up with impressive performance in 5G mm-wave arrays. Not much information has been made public but we have been impressed by the rapid pace of their development and their array performance.

Murata/pSemi

Murata is a leader in LTCC packaging for RF modules, and their US subsidiary (pSemi, formerly known as Peregrine Semiconductor) has some interesting ideas about how to put together active and passive components for high volume/low cost production.

Netgear

Netgear has introduced a first 5G mm-wave mobile hotspot for AT&T at 39 GHz, but the performance is very low with EIRP of only +15 dBm listed in the FCC documentation. We expect them to find different RF solutions and try again.

Nokia

Nokia is a strong base station vendor with a strong end-to-end product portfolio and a good integrated strategy for 5G.

Nokia dropped out of the market for 5GTF hardware in the US FWA market, deciding instead to focus on 5G NR development. The company plans to introduce multiple products for the rooftop level and for 'street level' deployment, but was not ready to release public info in March 2019. They had filed some public information with FCC that indicates competitive performance for mm-wave radio.

Nuvotronics

Nuvotronics constructs steerable antenna arrays for military (radar) applications, and has experience with the integration of antennas, filters, power amplifiers, LNAs, and back-end processing in heterogeneous assemblies. Nuvotronics is in a good position to offer know-how to the industry when it comes to buried waveguide transmission lines, antenna arrays, and heat management in a very small mm-wave assembly.

NXP

NXP sells integrated modules for automotive radar applications at 77 GHz, and thus has a strong mm-wave production capability. The company is a leading supplier of power amplifiers in frequency bands below 5 GHz, but we have not seen mm-wave solutions for 5G yet.

Pivotal Commware

Pivotal Commware is a Bill Gates-backed startup company that develops 'holographic beamformers', which operate on a different principle than other beamformers on the market. The holographic beamformer uses a small number of RF front ends, with a waveguide structure that has multiple 'tap points' spaced cleverly along an array, to form a steerable beam with low EVM distortion.

Qorvo

Qorvo supplies GaN devices and several other compound semiconductor MMICs, with clear experience in both government and commercial markets. Qorvo is working with multiple OEMs on mm-wave 5G prototyping, using GaN devices.

Qualcomm

Qualcomm has established a clear lead in 5G modems, and in fact they've recently introduced their second-generation modem with multi-mode (2G/3G/4G/5G) support as well as beamforming coordination. In addition, the company has RFICs available that integrate up/downconversion, power amplifier/LNA, and antennas at 28 GHz, with a thoughtful approach to the use of multiple mm-wave RFICs in a handset.

Qualcomm also offers a small-cell SoC for the infrastructure side which is currently aimed primarily at the market below 6 GHz. However, the FSM100 chipset could lead to a position in CPEs for Qualcomm in the mm-wave market as well.

Qulsar

Qulsar has developed a cost-efficient solution for 5G synchronization which addresses the issues with tigher timing and phase synchronization that come along with 5G radio implementation. Qulsar products include clocks, software-based sync solutions for small cells, and grandmaster solutions.

Samsung

Samsung jumped into the mm-wave bands early, and their advanced research work is now paying off. The company's 5G mm-wave radio units are smaller and more efficient than any other radios on the market. Samsung achieved this with some early internal RF-SOI development work and very large arrays. To optimize their product over time, we expect Samsung to move away from the internal RF-SOI process and use other, more production-scalable processes.

Samsung has taken the leading role in the Verizon 5GTF and now 5G NR deployment, with roughly half of the announced cities so far. The company claims to have shipped 36,000 5G base stations as of February 2019 (we interpret this to mean 36,000 radio units at all frequencies, including 4G units upgradable to 5G)

Samsung clearly has a leading position in smartphones and tablets, and the company can be expected to support 5G mm-wave CPEs, handsets, and possibly hotspot solutions.

Xilinx

The Xilinx RFSoC handles a wide bandwidth and could become a leading contender to perform the data conversion and basic up/downconversion functions of the RU, along with an up/downconverter to set the RF frequency to 24 or 28 GHz as needed.

ZTE

ZTE is a major RAN vendor but they're not on the radar screen for mm-wave equipment. ZTE has no hope of selling a 5G base station in the USA, so we don't expect them to invest in this opportunity for the next few years. They should get involved when the Chinese market begins to move into mm-wave bands in the 2024-2025 timeframe.

11 METHODOLOGY

For our 5G mm-wave analysis, we reset our analysis this year by investigating the need for mm-wave capacity for major US operators. Based on ROI analysis confirmed through discussions with operators and major OEMs, we convinced ourselves that mm-wave gNodeB capacity will be necessary for mobile operators to continue their consolidation of the communications market.

Based on the demand vs capacity model, we set our forecast to balance a few factors:

- How much capacity the operators need to keep up with demand;
- What is the availability of fiber and small cell site locations?
- How quickly do the operators need to get mm-wave capacity in place?

Finally, we interviewed more than 30 semiconductor and component suppliers to understand the limitations of physics. Can silicon deliver high EIRP without too much heat load? What is the optimal configuration of Massive MIMO for power consumption? How much will mm-wave radios cost in a handset? These types of questions establish an understanding of what's possible with state-of-the-art hardware.

The bottom line: Our forecast is based on estimates of:

1. Traffic density and estimated numbers of sites that need 5G capacity upgrades to satisfy end-user demand;
2. Network cost calculations and estimates of how many sites have a positive ROI from 5G upgrades;
3. Cost estimates for CPE and mobile devices, and expected adoption rates;
4. Estimates of the ability for the supply chain to deliver large quantities of components in production.

12 Appendix: Photos of m-MIMO Hardware

Infrastructure examples

Figure 36. Nokia mMIMO array, 28 GHz band, +55 dBm linear EIRP

Source: Mobile Experts (Feb 2019 photo)

Figure 37. Samsung RRH at 28 GHz, 2 beams/4 streams at +60 dBm linear EIRP total

Source: Mobile Experts, Feb 2019 photo

Figure 38. Samsung RRH at 39 GHz, one beam (two streams) at +50 dBm linear EIRP

Source: Mobile Experts, Feb 2019 photo

Figure 39. Samsung RRH at 28 GHz, one beam (2 streams) using cable-strand mounting

Source: Mobile Experts, Feb 2019 photo

Figure 40. Ericsson 2018 mMIMO array, 192 elements at 28 GHz at +56 dBm EIRP (2018)

Source: Mobile Experts (Feb 2018 photo)

Figure 41. Ericsson mMIMO array, 192 elements at 28 GHz with baseband processing (2018)

Source: Mobile Experts (Feb 2018 photo)

Figure 42. Ericsson mMIMO array, +60 dBm with active cooling (fans on back)

Source: Mobile Experts (Feb 2019 photo)

Figure 43. Huawei mMIMO array at 28 GHz

Source: Mobile Experts (Feb 2019 photo)

Figure 44. Intel Repeater at 28 GHz, low cost implementation

Source: Mobile Experts (Feb 2019 photo)

Figure 45. An infrastructure product from Movandi

Source: Movandi

CPEs and User Equipment (UE)

Figure 46. Samsung outdoor and indoor CPEs for fixed wireless at 28 GHz (2018)

Source: Samsung, Feb 2018

Figure 47. Samsung Outdoor CPE

Source: Mobile Experts (Feb 2019)

Figure 48. Samsung indoor CPE units

Source: Mobile Experts Feb 2019 photo

Figure 49. The Netgear mm-wave mobile hotspot

Source: Netgear

Figure 50. The Motorola 5G MOD product, 28 GHz

Source: Motorola